Better Understanding of Soil Resources – Dune Stabilisation and Rates of Soil Development on Welsh Dune Systems

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CRYNODEB WEITHREDOL

1. Amcan yr astudiaeth hon oedd canfod graddau datblygiad pridd mewn systemau twyni yng Nghymru i ddibenion rheolaeth a chadwraeth ansawdd pridd a'r cymunedau llystyfiant cysylltiedig yn y cynefinoedd hyn.

2. Yn sail ar gyfer yr astudiaeth hon defnyddiwyd data pridd o ddau safle, Cwningar Niwbwrch a Merthyr Mawr, a gedwir gan y Ganolfan Ecoleg a Hydroleg ym Mangor. Pennwyd oed pridd yn y safleoedd samplu hyn trwy ddefnyddio lluniau awyr, mapiau a ffynonellau hanesyddol eraill. Rhoddodd y data sylweddol a oedd ar gael ar gyfer Cwningar Niwbwrch gronoleg fanwl yn ôl i 1945, gyda chydraniad amserol o tua 5 - 10 mlynedd. Nid oedd data cystal ar gael ar gyfer Merthyr Mawr, felly mae'r dadansoddiad yn canolbwyntio'n bennaf ar ddata Niwbwrch.

3. Roedd data o bennu oedran y lleoliadau samplu hefyd yn dangos y modd roedd llystyfiant wedi ymsefydlu ar dywod noeth yn Niwbwrch dros amser. Dechreuodd sefydlogi 10 mlynedd cyn y clefyd mycsomatosis ac mae newidiadau yn y gyfradd sefydlogi'n dangos cyswllt cryf â ffactorau hinsoddol (cyflymder gwynt, glawiad, tymheredd) a grynhoir yn *Talbot's Mobility Index.*

4. Mae pridd yn datblygu ar hyd cromlin sigmoidaidd. Ychydig iawn o fater organig sy'n crynhoi yn yr 20 mlynedd gyntaf, gyda phridd yn ffurfio'n gyflym dros y 40 mlynedd nesaf. Yna, mae mater organig pridd sy'n crynhoi fel pe bai'n gwastatáu ar ôl tua 60 mlynedd. Mae'r data sydd ar gael ar gyfer Merthyr Mawr yn cadarnhau siâp ac uchder y gromlin, gan awgrymu dylanwadau ar raddfa fawr, a heb fod yn lleol, ar ddatblygiad pridd.

5. Mae cyfraddau datblygiad pridd yn gwahaniaethu rhwng cynefinoedd twyni sych a gwlyb. Mae pridd yn datblygu'n gyflymach mewn cynefinoedd gwlyb, gan gyrraedd cynnwys mater organig o 5% a thrwch FH o 6cm erbyn tua 60 mlynedd, o'i gymharu â chynnwys mater organig o 3% a thrwch FH o 4cm mewn cynefinoedd twyni sych dros yr un cyfnod o amser.

6. Mae cymharu cronoddilyniannau eraill y ceir gwybod amdanynt mewn llenyddiaeth o Brydain ac Ewrop yn cadarnhau siâp sigmoidaidd y gromlin. Tra bo diffyg cydraniad cymharol yn gwneud cymhariaeth uniongyrchol yn anodd, mae'n ymddangos bod datblygiad pridd yn Niwbwrch yn gyflymach yn y twyni sych nag mewn astudiaethau eraill, tra bo datblygiad pridd yn arafach yn y twyni gwlyb. Efallai mai'r rheswm am hyn yw bod cronoddilyniannau eraill o laciau twyni yn dilyn achosion o dorri tyweirch, sydd fel rheol yn gadael is-haen wedi ei datgalchu gyda pheth maetholion gweddillol.

7. Archwiliwyd ffactorau ffisigo-gemegol yn effeithio ar gyfradd datblygiad pridd yn y 60 mlynedd gyntaf. Yn yr hinsawdd twyni sych, roedd pellter i'r môr ac uchder llystyfiant yn ffactorau o bwys. Roedd datblygiad pridd yn gyflymach mewn cyfnodau gwlypach ac oerach, ac fel yr eid ymhellach o'r môr. Roedd perthynas negyddol ag uchder llystyfiant, efallai o ganlyniad i *Ammophila* creiriol ar briddoedd gwael a chwningod yn pori ar briddoedd ffrwythlon. Nid oedd ongl llethrau a'r cyfeiriad roeddent yn ei wynebu yn bwysig. Yn yr hinsawdd llaciau twyni roedd pH pridd ac uchder llystyfiant yn ffactorau pwysig. Roedd datblygiad pridd yn gyflymach mewn cyfnodau oerach ac ar pH is, efallai'n adlewyrchu rheolaeth dros gyfradd dadelfeniad. Yn y naill na'r llall o'r mathau

cynefin, nid oedd dyddodiad N, naill ai yn is neu'n union o fewn ffiniau isaf yr amrediad llwyth critigol, yn egluro cyfran sylweddol o'r amrywiad yn y 60 mlynedd gyntaf. Fodd bynnag, mae gwaith modelu'n awgrymu effeithiau tymor hwy ar welltiroedd twyni sefydledig (gweler pwynt 12 isod).

8. Edrychwyd hefyd ar fath llystyfiant a rheolaeth. Mae data o astudiaethau eraill yn awgrymu bod math llystyfiant yn elfen bwysig mewn ffurfio pridd. Fodd bynnag, nid oedd yn bosibl astudio hyn yn Niwbwrch oherwydd anghysondeb rhwng dulliau samplu pridd ar gyfer y goedwig a'r Gwningar. Roedd priddoedd o arbrawf pori 20 mlynedd yn Niwbwrch yn dangos nad oedd unrhyw wahaniaethau o bwys o ganlyniad i ddefaid yn pori ar y priddoedd hŷn hyn; o fewn lleiniau, roedd amrywiant o ganlyniad i leithder yn llawer mwy na'r gwahaniaethau bychain a briodolid i bori. Roedd data o briddoedd teneuach ym Merthyr Mawr yn awgrymu y gall cwningod yn pori dros gyfnod cyffelyb arafu crynhoad mater organig.

9. Mae cysylltiad agos rhwng olyniaeth llystyfiant yn y twyni sych a datblygiad pridd. Mae cyfnod cyflym datblygiad pridd yn digwydd yn bennaf o fewn cymunedau SD7, gan ddatblygu'n laswelltir twyni sefydlog SD8 ymhen tua 60 mlynedd. Nid oes cydberthynas rhwng cyfoeth rhywogaethau a chynnwys mater organig pridd, sy'n awgrymu bod ffactorau eraill yn chwarae rhan bwysicach. Mae cyfoeth rhywogaethau'n cynyddu gydag oed pridd. Fodd bynnag, mae gan gymuned SD19 flynyddol y twyni gyfoeth rhywogaethau arbennig uchel a all fod yn flaenoriaeth ar gyfer cadwraeth. Yr awgrym cryf yw bod rheoli'r cymunedau SD7 yn allweddol i reoli cynnydd datblygiad pridd.

10. Nid yw olyniaeth llystyfiant yn y twyni gwlyb yn gysylltiedig â datblygiad pridd. Nid oes cydberthynas rhwng cyfoeth rhywogaethau naill ai ag oedran pridd na chynnwys mater organig. Mae angen gwneud mwy o waith i ddeall y rheolaethau ar ddatblygiad llystyfiant yn y cynefin hwn.

11. Cyfraddau crynhoi cymedrig N yw 26.3 (amrediad 13.7 - 45.0 kg N ha^{-1} yr^{-1}) yn y twyni sych a 30.2 (amrediad 11.9 - 57.5 kg N ha^{-1} yr^{-1}) yn y llaciau twyni. Mae'r cyfraddau hyn 2.5 - 3 gwaith yn fwy na chyfanswm mewnbwn N atmosfferig ac yn arwydd o ffynhonnell ychwanegol sylweddol o N, efallai o sefydlogiad N biolegol, er y gall haenau pridd o dan yr wyneb a dŵr daear gyfrannu hefyd.

12. Mae rhagweld datblygiad pridd yn y dyfodol yn dibynnu i raddau helaeth ble mae eich man cychwyn. Mae'r cronoddilyniannau'n awgrymu datblygiad pridd cymharol araf ar ôl 60 mlynedd. Fodd bynnag, cyfrifir y gall N ychwanegol o ddyddodiad atmosfferig ar lefelau 20 kg N ha^{-1} yr^{-1} (dwbl y dyddodiad presennol yn Niwbwrch neu Merthyr Mawr) ychwanegu 15 % at gynnwys mater organig pridd glaswelltir sych sefydledig dros gyfnod o 100 mlynedd.

13. Trafodir strategaeth fonitro bosibl ar gyfer priddoedd twyni Cymreig. Argymhellir strategaeth eang cyn gynted â phosibl i sefydlu amodau pridd a llystyfiant cysylltiedig ar draws amrediad o systemau twyni yng Nghymru. Mae'r man cychwyn hwn yn angenrheidiol i ragweld newid yn y dyfodol. Dylid cynnal yr arolwg drachefn bob tua 10 mlynedd. Ceid gwerth ychwanegol sylweddol trwy gyfateb y trefniadau samplu a dadansoddi â'r Arolwg Cefn Gwlad presennol, sydd hefyd yn cael ei gynnal ar draws Cymru mewn 100 o sgwariau. Gallai'r opsiwn symlaf ar gyfer gwirio cyflwr safleoedd naill ai ddefnyddio %LOI, wedi ei bennu yn y mesuriadau labordy maes o drwch FH, a

chymharu hynny yn erbyn cromliniau datblygiad pridd neu gynnwys mater organig cymedrig ar gyfer amrediad o gymunedau llystyfiant twyni sych.

14. I gloi, mae'r astudiaeth hon wedi rhoi gwybodaeth newydd bwysig ar y prosesau sy'n ymwneud â rheoli camau cynnal datblygiad pridd mewn twyni tywod, gyda goblygiadau ar gyfer rheoli datblygiad pridd a'r cymunedau llystyfiant cysylltiedig. Tra na ellir cael fawr o reolaeth dros rai o'r prif ddylanwadau, megis hinsawdd, gall rheolwyr safle ddylanwadu ar ddatblygiad pridd trwy ddulliau rheoli wedi eu hanelu at arafu camau cynnar olyniaeth ac annog tarfu eilaidd mewn systemau sydd wedi gor-sefydlogi.

EXECUTIVE SUMMARY

1. This study aimed to ascertain rates of soil development in Welsh dune systems in order to inform the management and conservation of soil quality and the associated vegetation communities in these habitats.

2. Spatially referenced soil data held by the Centre for Ecology and Hydrology Bangor for two sites, Newborough Warren and Merthyr Mawr, which were used as the basis for this study. Soil ages at these sampling locations were established using aerial photographs, maps and other historical sources. The high data availablility for Newborough Warren provided a detailed chronology back to 1945, with a temporal resolution of around 5 – 10 years. Data availability for Merthyr Mawr was poorer, therefore analysis focuses mainly on the Newborough data.

3. Data from ageing the sampling locations also showed the progression of vegetation establishment on bare sand at Newborough over time. The onset of stabilisation preceded myxomatosis by 10 years and changes in the rate of stabilisation show a strong link to climatic factors (windspeed, rainfall, temperature) summarised in Talbot's Mobility Index.

4. Soil development proceeds along a sigmoidal curve, with very little organic matter accumulation in the first 20 years, followed by rapid soil formation over the following 40 years, and a subsequent levelling off of soil organic matter accumulation beyond around 60 years. The data available for Merthyr Mawr confirm both the shape and height of the curve, suggesting large scale, non-local, influences on soil development.

5. Rates of soil development differ between dry and wet dune habitats. Soil develops at a greater rate in wet habitats, reaching an organic matter content of 5 % and FH horizon thickness of 6 cm by around 60 years, compared with an organic matter content of 3 % and FH horizon thickness of 4 cm in the dry dune habitats over the same timescale.

6. Comparison of other chronosequences reported in the literature for UK and Europe confirm the sigmoidal shape of the curve. While the lack of comparable resolution makes direct comparison difficult, soil development at Newborough appears to be faster in the dry dunes than in other studies, while in the wet slacks soil development is slower. This may be because other published slack chronosequences follow sod-cutting episodes, which usually leave a de-calcified substrate with some residual nutrient load.

7. Physico-chemical factors affecting the rate of soil development in the first 60 years were examined. In the dry dunes climate, distance to the sea and vegetation height were significant factors. Soil development was faster in wetter and in colder periods, and at increasing distance from the sea. There was a negative relationship with vegetation height, possibly due to relict *Ammophila* on poor soils, and rabbit grazing on fertile soils. Slope angle and slope aspect were not significant. In the dune slacks climate, soil pH and vegetation height were significant factors. Soil development was faster in cooler periods and at lower pH, possibly reflecting controls on decomposition rates. In neither habitat type did N deposition, below or just within the lower bounds of the critical load range, explain a significant proportion of the variation in the first 60 years. However, modelling work suggests longer term impacts on established dune grassland (see point 12 below).

8. The effects of vegetation type and management were also examined. Data from other studies suggest that vegetation type plays a major role in soil formation, however it was not possible to study this at Newborough due to inconsistency between soil sampling methods for the forest and Warren. Soils from a 20-year grazing experiment at Newborough showed that there were no significant differences due to sheep grazing in these older soils; within plot variability due to moisture availability was much greater than the slight differences attributable to grazing. Data from thinner soils at Merthyr Mawr suggest that rabbit grazing over a similar timescale may slow down organic matter accumulation.

9. Vegetation succession in the dry dunes is closely linked to soil development. The rapid phase of soil development occurs mostly within SD7 communities, developing into SD8 fixed dune grassland by around 60 years. Species richness is not correlated with soil organic matter content suggesting that other factors play a greater role. Species richness increases with soil age, however the dune annual SD19 community has a particularly high species richness which may be a priority for conservation. The strong implication is that management of the SD7 communities is key to controlling the progression of soil development.

10. Vegetation succession in the wet dunes is not linked to soil development. Species richness is not correlated with either soil age or organic matter content. More work is required to understand the controls on vegetation development in this habitat.

11. Calculated mean N accumulation rates are 26.3 (range 13.7 – 45.0 kg N ha^{-1} yr^{-1}) in the dry dunes and 30.2 (range 11.9 – 57.5 kg N ha^{-1} yr^{-1}) in the dune slacks. These rates are 2.5 – 3 times the total atmospheric N input and point to a significant additional source of N, probably from biological N fixation, although buried soil layers and groundwater may also contribute.

12. Predictions of soil development into the future depend largely on where your starting point is. The chronosequences suggest relatively slow soil development beyond 60 years, however it is calculated that additional N from atmospheric deposition at levels of 20 kg N ha^{-1} yr^{-1} (double the current deposition at Newborough or Merthyr Mawr) could add 15 % to the organic matter content of an established dry grassland soil over a 100 year period.

13. A potential monitoring strategy for Welsh dune soils is discussed. A broad survey is recommended as soon as possible to establish soil and associated vegetation conditions across a range of Welsh dune systems. This baseline is necessary for determining change in the future. The survey should be repeated approximately every 10 years. Considerable extra value would be gained by matching the sampling procedures and analysis to the current Countryside Survey, which is also being conducted across Wales in 100 squares. The simplest option for checking site condition could use either %LOI determined in the laboratory field measurements of FH horizon thickness, and comparison against presented soil development curves or mean organic matter contents for a range of dry dune vegetation communities.

14. In conclusion, this study has provided important new information on the processes controlling the early stages of soil development in sand dunes, with implications for managing soil development and the associated vegetation communities. While there can be little control over some of the major influences such as climate, site managers can influence soil development by management practices aimed at retarding early phases of succession and encouraging secondary disturbance in over-stabilised systems.

CONTENTS

1. OBJECTIVES AND PROJECT SPECIFICATIONS AS OUTLINED IN THE TENDER.

1.1 Objectives

The objectives of this study, as defined in the tender were,

1. To inform the future strategic management of Welsh dunes by characterising the current rate of soil development on Welsh dunes and the likely further changes over the next 100 years if these trends continue.
2. This will underpin the future management measure aimed at protecting the soils which underpin the mobile, semi-mobile and fixed dune habitats.
3. The study will be based on the analysis of existing information on two key dune systems, namely Merthyr Mawr and Newborough. Information on the latter will be derived from a variety of studies undertaken in the past by CEH Bangor and its predecessors not all of which is in the public domain. A secondary objective is to bring more of this information onto the public domain and ensure it is not lost.

1.2 Suggested methodology

1.2.1 Review soil data for Merthyr Mawr collected as part of the nutrient study which CEH carried out for CCW (Jones *et al.*, 2005). Classify different profiles obtained and relate to likely age of profile ascertained from aerial photographs and sea buckthorn survey data, archaeology studies and any other relevant data sets.

1.2.2 Estimate rates of soil formation at Merthyr Mawr.

1.2.3 Review available soil data for Newborough Warren related to past work by CEH and its predecessor organisations. This should include work related to past grazing experiments and relate to possible age of soils as ascertained from aerial photography past surveys etc

1.2.4 Estimate rates of soil formation at Newborough

1.2.5 Compare findings for Merthyr Mawr and Newborough with available data in the literature on dune soil development.

1.2.6 Review the level of nutrients attached to each stage of soil development and draw any relevant conclusions with respect to habitat change.

1.2.7 Based on the results from the above identify a cost effective methodology for determining/monitoring the rate of soil development on welsh dune systems and indicate the level of accuracy and precision attached to such a method.

1.2.8 Using the findings of this study extrapolate likely rates of soil development for Merthyr Mawr for twenty, fifty and one hundred years hence assuming no change in current rates of atmospheric nutrient inputs and management.

1.2.9 Draw conclusions on the likely resulting habitat changes over these time frames.

2. INTRODUCTION

2.1 Background

Sand dune habitats in Wales are becoming increasingly stabilised, resulting in altered geomorphology and defining biological features. The dynamic and changeable nature of the habitat is inherently required by the many rare and protected species that struggle to maintain a foothold on these increasingly stabilised systems. As a result, some sand dune SACs are now classified as being in unfavourable condition. Creating strategic management plans for these habitats is difficult however, as we lack the basic understanding of soil formation in dune systems and how this influences dune stabilisation and habitat change. It is thought that the increasing rates of stabilisation are a result of increased nutrient input, management changes and climate change. In combination, these drivers could result in rapid development of soil.

2.2 Dynamic dune systems

Dune systems are inherently dynamic, albeit over many different spatial and temporal scales. Mobility is ultimately controlled by sediment supply and climate over geological timescales (Carter, 1988). However, within the last thousand years man has had increasing influence on these natural systems and contributed to their relative stability or instability, through practices such as grazing, cutting marram for thatch, warrening and more recently through development, tourism pressure and conservation management practices.

2.3 Stabilising factors

Stabilisation of sand dunes, including soil formation, means an increasing loss of habitat for pioneer and colonising species as the dune system changes and matures. Also lost with increased stabilisation are the young soils that characterise these habitats; so as well as a loss in biodiversity, increased stabilisation will result in a loss of geodiversity.

Sand dunes become stable when perennial plants colonise, beginning the process of soil formation. Soil formation is dependent on organic matter accumulation (Sevink, 1991), which in turn is highly dependent on climate (see below). Availability of water is key at this stage of stabilisation, with soils with a very low water-holding capacity and high levels of drainage dependent primarily on rainfall (unless the ground water table is very shallow). The ratio between precipitation and evapotranspiration (which is the sum of evaporation and ecosystem transpiration) is key to plant growth and development (Sevink, 1991).

Stabilisation of sand dunes is a natural process, however it has been observed to increase markedly in recent years. Increased stabilisation of dune systems has been attributed to higher nutrient loads, altered land management and climate change. However few studies have been carried out into this, and therefore existing discussions on the rate of stabilisation of dunes at present remain largely theoretical (Sevink, 1991) often based on research in very different habitats with different climates (ie continental sand dunes systems) and long term chronosequences over thousands or even tens of thousands of years (Syers *et al.*, 1970).

2.4 Nutrient enrichment

Increased dominance of fast growing graminoid species, such as *Ammophila arenaria*, have been linked to enhanced deposition of atmospheric nitrogen (Ketner-Oostra *et al.*, 2006). Atmospheric nitrogen deposition is implicated as a factor causing alterations to dune vegetation and soils (Kooijman, 2004), although much of this evidence has been anecdotoal, or based on extrapolation from effects seen in other semi natural habitats. Only recently has there been much empirical evidence to support this from survey based studies in the UK (Jones *et al.*, 2004) and from mesocosm studies in the Netherlands (van den Berg *et al.*, 2005). A nitrogen and grazing study in the Netherlands also showed changes in biomass but suggested that the results of N deposition were entirely mitigated by grazing (ten Harkel & van der Meulen, 1996). Work by Jones et al., (2004) showed correlations between increasing N deposition and increased above ground biomass in mobile and semi-fixed dunes, coupled with decreases in species richness in fixed dune grasslands. These effects would be expected to result in increased quantities of biomass entering the soil system, and therefore contributing to build up of organic matter and hence faster rates of soil formation. As well as directly affecting input of organic matter to the system, N deposition may indirectly control rates of decomposition. As N deposition increases in other ecosystems, this progressively leads to a reduction in the C:N ratio of the litter layer, partly as a result of higher tissue N contents in litter fall, but possibly also through alterations in the soil microbial community. These secondary effects are complex, and there remains considerable uncertainty as to how N deposition affects soil processes in dune systems. Jones et al. (2004) found an increasing C:N ratio and decreasing available inorganic N in the soil with increasing N deposition. Both of these relationships are the opposite to those observed in other semi-natural systems in the UK affected by N deposition. The mechanisms in dune systems by which N deposition may affect rates of soil development are therefore complex and require further research. However, N deposition is clearly one factor which may alter rates of soil development, both directly and indirectly.

2.5 Land management

Various anthropogenic activities can influence the stabilisation of sand dunes. In the past, stabilisation has been a preferred management option in some locations. For example in Newborough in the 1950s the land managers were actively attempting to stabilise the central and western areas of the dunes, predominantly through thatching and planting (Ranwell, 1959).

Grazing livestock and rabbits have generally been thought to help maintain the required instability needed in dune systems through creations of bare patches of sand and therefore habitats for pioneer species, as well as a source of sand for the general aeolian processes (Ketner-Oostra *et al.*, 2006). Indeed, overgrazing by domestic animals on dunes on San Miguel Island, California in the 1850s resulted in severe destabilisation of the natural ecology of the island, leading to a ‘barren waste of drifting sand and blowing soil’. Once the livestock was removed, re-colonisation by vegetation was ‘dramatic’ (Erlandson *et al.*, 2005).

Rabbit populations were high in the Newborough area in the early 1950s; it was reported that in 1954 as many as 300 individuals could be observed from one vantage point (Ranwell, 1959). However, an outbreak of the viral infection, myxomatosis, decimated the population in 1954, and by 1959 ‘vigorous vegetation growth’ was observed (Ranwell, 1959). Similar effects were also observed on the Norfolk coast at Blakeney (White, 1961). ten Harkel & van der Meulen (1996) observed that a decrease in rabbit population through viral disease further increased the dominance of graminoid grasses, already stimulated in the Dutch coastal dunes through high levels of nitrogen deposition.

2.6 Climate

Climate is a key controlling factor for coastal sand dune ecosystems, as in all terrestrial ecosystems. Movement of sand, key to the dynamic nature of these habitats, is influenced by wind, rainfall and soil/sand moisture. Plant growth, which itself influences the movement of sand and the very nature/structure of the dune landscape, is also influenced by wind, rainfall and soil moisture. Other climate variables such as soil temperature also influence plant growth (Sevink, 1991).

In terms of stability of dune structures, wind and precipitation have been shown to be key climate variables. Mobility indices have been developed for continental dune systems, which relate the mobility of sand to wind speed, precipitation and other climate variables. There are several versions on a similar theme, however all consider a threshold above which sand is blown, alongside precipitation and some value of evapotranspiration (which strictly defined is the sum of evaporation and ecosystem transpiration; i.e. the loss of water from the ecosystem into the atmosphere). An example is the Talbot (1984) Index:

$$M = V^3 / Mo^2$$

Where: $$Mo = \sum 115 * \frac{(P)^{1.111}}{T - 10}$$

Where V is the mean wind speed (mph), Mo is the moisture index, P is the precipitation value (in./month) and T is the monthly temperature (^{o}F/month). Dunes are classified as stable when M is below 1, semi-active when M is between 5 and 10 and fully mobile when values are in excess of 10 (Knight *et al.*, 2004).

There has been criticism of the various mobility indices however, for example in Lancaster & Helm (2000) the Lancaster Index was only useful when considered over decades rather the inter-annual response to climate, because of the lag in response of vegetation to various climatic events (such as drought). Tsoar (2005) pointed out that it takes much higher wind speeds to destabilise a vegetated dune compared with that needed to transport sand from a bare dune as the vegetation buffers and reduces the wind at the soil/sand level. Therefore, vegetation cover becomes key to determining the thresholds for wind speed or the levels of indices into which the dunes are classified. Hesse & Simpson (2006) considered vegetation cover to be more important than wind speed, with respect to stabilisation of dunes in eastern, central Australia. However, conversely Levin et al. (2006) found wind speed to be the limiting factor to sand movement/destabilisation in coastal dunes in Israel. Hugenholtz & Wolfe (2005) found that in the continental sand dunes of Canadian prairies cooler temperature and/or greater precipitation increased stabilisation, and this was reflected when considering the changes over time as well as comparing different sites with variable climate. Clearly much variability exists between different dune systems. While such indices were developed for predicting large scale mobility in desert systems, and the thresholds for mobility of the system (i.e. Mo=1 in the Talbot Index) have limited relevance to coastal dunes in a temperate climate, the basic principles apply and calculating the index still provides useful information on the likely influence of climate on sand dune mobility and stabilisation for the west coast of the UK.

There has been little work carried out on the initial stages of soil formation on stabilising sand dunes (Sevink, 1991). As described above, as perennial plants colonise the soil, they grow and produce litter (both above ground, and below-ground as dead roots). The organic matter content of the sand/soil increases as the plant litter decomposes producing humus. Climate has a very strong influence over litter decomposition, in particularly *via* soil temperature and the availability of water (Sevink, 1991).

As well as affecting the basic conditions governing mobility of sand dunes, climate also affects rates of soil development once stabilisation by vegetation has commenced. The ratio between precipitation and evapotranspiration (which is the sum of evaporation and ecosystem transpiration; i.e. the loss of water from the ecosystem into the atmosphere) is absolutely key to plant growth and development. Prolonged drought can cause a reduction in plant biomass production and lower rates of organic matter accumulation in the soil. Drying up of dune slack habitats which are typically flooded for part of the year may also oxidise the soil and contribute to microbial decomposition of accumulated organic matter with a net loss of carbon from the system (e.g. droughts in peat/forest). On the other hand, excess water slows rates of decomposition, which can cause an increase in rates of accumulation of partially decomposed material (Sevink, 1991).

3. METHODOLOGY

3.1 Overview

This study aimed to ascertain rates of soil development in two dune systems for which a large amount of soil data was available from previous studies conducted by CEH, its predecessor organisations and other partners. These two dune systems were Newborough Warren, Anglesey, North Wales and Merthyr Mawr, South Wales. In order to examine rates of stabilisation and soil development in these two dune systems, the approximate age of the soil was estimated at all locations for which soil data existed. This was achieved using aerial photography records, maps and other historical data sources and reports which enabled dating of each location to varying degrees of accuracy. Relationships between soil age and soil parameters were then compared, and the implications for vegetation community development also investigated.

The methodology differs somewhat from that suggested by CCW in the tender document. This is primarily due to availability of data and the time taken to process it. Extensive aerial photography records were available for Newborough Warren, access to which was very kindly arranged by John Ratcliffe. Newborough also had a greater number of locations of soil sampling, including data from a study of the Newborough forest soils in 1986/7, allowing some repeat sampling over time which in theory provides considerably more potential for interpretation of controlling factors. It proved far more time consuming to date individual locations than at first envisaged. There are several reasons for this. Firstly, there were delays in CCW providing the 2000 GetMapping aerial photography data which was necessary for accurate matching of GPS co-ordinates to individual morphological features, in order to then trace these locations back in time. Secondly, dune systems are highly dynamic and these morphological features change over time as individual landforms mobilise and/or develop. Thus, it was sometimes difficult to ascertain precise locations for some samples in older aerial photographs. Thirdly, while GPS co-ordinates were available for all the sampling locations from 2002 onwards, these are still only accurate to ± 10 metres. In the context of the highly heterogenous topography of dune systems, a lateral difference of 10 m could make the difference between locating a point within a dune slack, a steep semi-fixed dune slope or the more stable fixed dune grassland at the top of a dune. Thus, considerable care was needed to interpret ages of soil locations in or near such transitional habitats, particularly in the context of migrating dune features over time.

For these reasons, the bulk of the study concentrates on developing the basic relationships between soil development and explanatory environmental factors using data from Newborough Warren. The data from Merthyr Mawr, for which there are fewer soil locations and a less complete aerial photography record, are used to support these findings.

3.2 Sources of soil data and associated environmental information

3.2.1 Existing data

CEH holds a range of spatially referenced soil data for Newborough Warren, as maps or GPS co-ordinates, collected as part of the following studies: A study of Newborough forest soils, with some comparative samples collected in the Warren area (Hill & Wallace, 1987, 1989); a survey of 12 English and Welsh sand dune systems looking at impacts of N deposition on vegetation, groundwater and soils (Jones *et al.*, 2002; Jones *et al.*, 2004); a study of soil requirements for rare species in 12 UK sand dune sites (ongoing); an ongoing Nitrogen x grazing manipulation experiment at Newborough (Plassmann, 2006); MSc and undergraduate project studies on the former ITE grazing plots at Newborough, experiment described in (Hewett, 1982, 1985). Soil data available for Merthyr Mawr were collected as part of the dune survey described above (Jones *et al.*, 2002), and a nitrogen budget study (Jones *et al.*, 2005). In addition, a number of additional locations were sampled at Newborough Warren as part of the fieldwork component of this project, described below. The final set of soil locations used in this analysis for Newborough Warren and Merthyr Mawr are shown in Appendix A.

3.2.2 Additional field sampling

The additional field sampling had three main aims: improving temporal resolution in the dune slacks, re-surveying the former ITE grazing plots, and trying to calibrate different soil sampling methods with respect to the Hill & Wallace forestry samples. The dune slack sampling concentrated on locations where clear stages of landform development, resulting in chronosequences of dune slack development, could be traced from the aerial photography record (see examples in Appendix B). The re-sampling of the ITE grazing plots was necessary for two reasons. Previous soil data collected on the old ITE grazing plots as part of an MSc project had been analysed separately by horizon and there was insufficient information to recombine the data into the format required for this exercise. Furthermore, differences between the replicate blocks meant that careful selection of sampling locations was necessary in order to account for topographical effects on soil development. The calibration exercise was necessary as it was subsequently discovered that the sampling methodology differed in the Hill & Wallace study from the CEH methods and the data were not comparable. It would also have been desirable to re-survey more locations within the forest. However, only 2 man-days were allocated to the additional field work and this limited us to around 40 extra samples.

Together with the additional field sampling and including the Hill & Wallace forestry data, there were 111 useable soil sample locations with %LOI and FH horizon thickness data, with supporting data which enabled more detailed interpretation. Information from other sites in the sand dune and rare species surveys provided a wider dataset which was useful to test relationships between the soil factors %LOI and FH horizon thickness, and associated soil and community characteristics such as species richness, NVC communities, and C and N accumulation rates.

3.2.3 Description of soil parameters and associated variables:

Soil parameters available for most locations were Loss on Ignition (LOI), and thickness of the organic (FH) layer. The data that had been collected by CEH used a consistent methodology, taking 5 cm diameter soil cores down to a depth of 15 cm. Data for Merthyr Mawr had been subsequently separated into FH and mineral horizons which were analysed separately, but were re-combined for this study using information about the thickness of each horizon. The sampling methodology for the Hill & Wallace study was slightly different, with soil samples taken at 5, 15 and 30 cm depths (Hill & Wallace, 1987). A calibration exercise, discussed in section 4.6.5, was undertaken in order to try and ensure data collected using both methods could be validly compared.

Other soil variables were available for some data points. These included soil pH, available nitrogen, %N and %C content, C:N ratio and these were also used in this study, together with information from the associated vegetation quadrats about biomass, species richness, slope, aspect and bare sand cover.

3.3 Aging the dunes

Table 1 shows full details of data sources used for dating the soil locations. Near-vertical aerial photos of Newborough Warren were available at varying intervals spanning the time period 1945 to 2000. Additional oblique photos from 1955, 1956 and partial aerial photos from 1957 were used for some sites to clarify time frames in between the aerial photo range. Luftwaffe photos from 1941 unfortunately covered only a small part of the site for which no soil samples existed and were therefore not used. Photos of Newborough gave an approximately 5 – 10 year resolution of change. Prior to 1941, Ordnance Survey Maps were available for Newborough Warren, dating back to around 1850. These maps showed some dune features within the Warren and symbols indicated a range of mobility in different parts of the Warren, although it was uncertain how accurate was the mapping of morphological features within the Warren. The later editions seemed to show no changes within the Warren from the First Edition of 1888 and it is possible that the Warren itself had not been re-surveyed. These maps were used to estimate minimum ages for areas of fixed grassland around the dune edges.

Fewer aerial photographs were available for Merthyr Mawr. These included near-vertical photos from 1947 and later images from 1991 onwards, with some oblique photography of the escarpment in 1974. Other photographs may have been available from the Central Register of Air Photography for Wales (CRAPW), Cardiff, but it was not possible to obtain them within the timescale of this study. Therefore, the coverage for Merthyr Mawr was poor and the data from Merthyr Mawr are used only to back up the findings from Newborough.

Table 1. Details of sources used to date soil locations at Newborough Warren and Merthyr Mawr.

Site and Year	Notes
Newborough Warren	
1850	OS Map.
1888	OS Map. OS First Edition, without contours, surveyed in 1887
1901	OS Map. Revised in 1899
1926	OS Map. Revised in 1915
1945	Aerial photos. Coverage of the Warren mostly complete but some gaps
1948	Aerial photos.
1951	Aerial photos.
1955	Oblique aerial photos.
1956	Oblique aerial photos.
1957	Aerial photos. Partial coverage
1960	Aerial photos. Coverage mostly complete but some gaps
1966	Aerial photos.
1970	Aerial photos. Some missing coverage
1971	Aerial photos.
1972	Aerial photos.
1975	Aerial photos. Some missing coverage
1982	Aerial photos. Some missing coverage, and parts obscured by cloud
1990	Aerial photos.
2000	GIS. GetMapping coverage
Merthyr Mawr	
1947	Aerial photos.
1974	Oblique aerial photos.View of escarpment only
1991	Aerial photos.
1995	Aerial photos.
2000	GIS. GetMapping coverage

The procedure for ageing soil locations was as follows. GPS co-ordinates for each soil sample location were input into a GIS, and matched to the most likely location on the 2000 GetMapping imagery using a combination of available information about the slope, aspect, habitat type and bare sand cover from the associated survey data. This was possible for all post-2000 soil locations sampled by CEH. For the 1987 Hill & Wallace locations which did not have GPS location data, it was found that some of the sampling descriptions did not match their approximate locations on maps in the report. Therefore, it was necessary to return to the original field notes and sketch maps to accurately re-locate many of these points. For some of these, accurate location was not possible and a best estimate was made. Once locations had been identified onto landforms in 2000, the vegetation cover at each point was estimated successively back in time using the aerial photographs. Vegetation cover was estimated to the nearest 10 %. Bare sand was recorded as 0 % vegetation cover.

A number of difficulties and methodological issues affect the accuracy of such an exercise. Estimating vegetation cover from aerial photographs can be rather crude. For example, areas which were known to be mobile sand but with a good cover of *Ammophila arenaria* when surveyed appeared fully vegetated in aerial photographs from that time period. In some aerial photographs locations next to tall morphological features were in shade, making it difficult to estimate vegetation cover. Varying contrast and resolution of the photographs between years also made consistent estimation of vegetation cover difficult, particularly at low levels of vegetation cover, due to over-exposure of the photographs with the glare from the dunes. In the dune slacks, the water table was particularly high in some of the earlier photographs, therefore it was not always possible to tell whether dark patches were vegetated or were simply flooded. Where possible this was resolved by looking for paler areas on the edge of slacks wetted by capillary rise and looking for patches of darker colour within these which would signify vegetation. Uncertainty here may contribute to variation in the estimated ages but comparison with photos at adjacent time points helped reduce this. Lastly, patchy hummocky vegetation was a common feature in the 1950s, with hummocks vegetated with *Salix* and *Ammophila* surrounded by bare sand, and it was not always possible to accurately determine whether a specific location was vegetated or not. Despite these methodological considerations, it is felt that in most cases the ages were estimated reliably to within 10 years.

3.4 Data analysis

In order to assess the likely influence of vegetation stabilisation on soil development, dates for each soil location were established for a) the first visible vegetation establishment, b) the time at which vegetation cover > 60 % and c) when the vegetation appeared fully fixed. For each of these time points, the photograph dates spanning that event give the maximum and minimum ages, and the average was taken for purposes of analysis. For example, if aerial photographs suggest that a location first became vegetated between 1960 and 1966. The date of first vegetation cover is then 1963 ±3 years and, if the location was sampled in 2006, the soil age is therefore 43 ±3 years. Subsequent analysis showed that the age since first vegetated provided the greatest information, and all analysis uses these ages, although section 4.2 provides an overview of the other data.

4. RESULTS

4.1 Interpretation of aerial photography at Newborough.

Analysis of aerial photographs from Newborough Warren shows progressive stabilisation of the dune system over time. Figure 1 shows the progress of vegetation development at each soil location, which gives a picture of a steady decline in mobility, with most stabilisation of the system occurring in the period from 1950 to 1970. Some locations show partial remobilisation, and this occurred particularly between 1945 and 1951, between 1965 and 1972, and post 1990. Otherwise however, stabilisation was more or less continuous. This is summarised in Figure 2, which shows the number of locations at any one time point which had bare sand (i.e. 0 % vegetation cover). Missing coverage for some aerial photographs was taken into account by extrapolating between years where that location was known to continue as bare sand. While these locations are not a random sample across the Warren, nevertheless the data suggest a more-or-less continuous decline in the amount of bare sand in the system.

One interesting observation from Figure 2 is that the onset of stabilisation appears to precede the arrival of myxomatosis at Newborough which, according to Ranwell (1960) arrived on Anglesey in 1954 and has been frequently cited as one of the major causes for rapid vegetation encroachment at the site. Ranwell conducted some vegetation surveys immediately prior to the arrival of myxomatosis at Newborough and suggested that no change in the vegetation had occurred by May of 1955. The oblique aerial photographs for 1955 were also taken in May. Therefore, the vegetation cover in 1955 can be interpreted as the pre-myxomatosis situation. Figure 2 shows a steep decline in area under bare sand from 1945 onwards, although the decline steepens still further after 1955 which coincides with the advent of myxomatosis. Figure 3 shows the same data overlain with the number of locations having over 30 % vegetation cover, and the Talbot's Mobility Index which is an index of the climatic factors affecting dune stability. There appears to be a roughly five year lag for vegetation cover to reach 30 % which is partly a function of the interval between years for which we have aerial photography coverage, but also suggests a maximum time of 5 years taken for vegetation cover to reach 30 %, once colonisation with vegetation has started. What this allows us to do is to look back slightly further in time than 1945. The flat slope at the start of this curve suggests that the onset of stabilisation occurred only a few years before 1945. Changes in the Talbot's Mobility Index (M), calculated for Newborough based on meteorological data from nearby RAF Valley, suggest a strong climatic control to dune stability. A run of low values of the index from 1946 to 1961 coincide with the period of most rapid stabilisation, and subsequent high values around 1970 coincide with a temporary respite in the spread of vegetation across the dunes, which is resumed around 1980 as the mobility index falls again. Although the index was designed to predict large scale dune mobility in arid systems in the Sahel region of Africa (with M values of under 1 indicating stability, $5 < M < 10$ indicating episodic stability, and $M > 10$ indicating full mobility, Talbot (1984)), it has merit in summarising the climatic factors most affecting dune stability and can give an accurate idea of the relative mobility, even in a temperate dune system with relatively high annual rainfall (> 800 mm p.a.) such as Newborough Warren. There are insufficient data at present to conduct the same exercise for Merthyr Mawr.

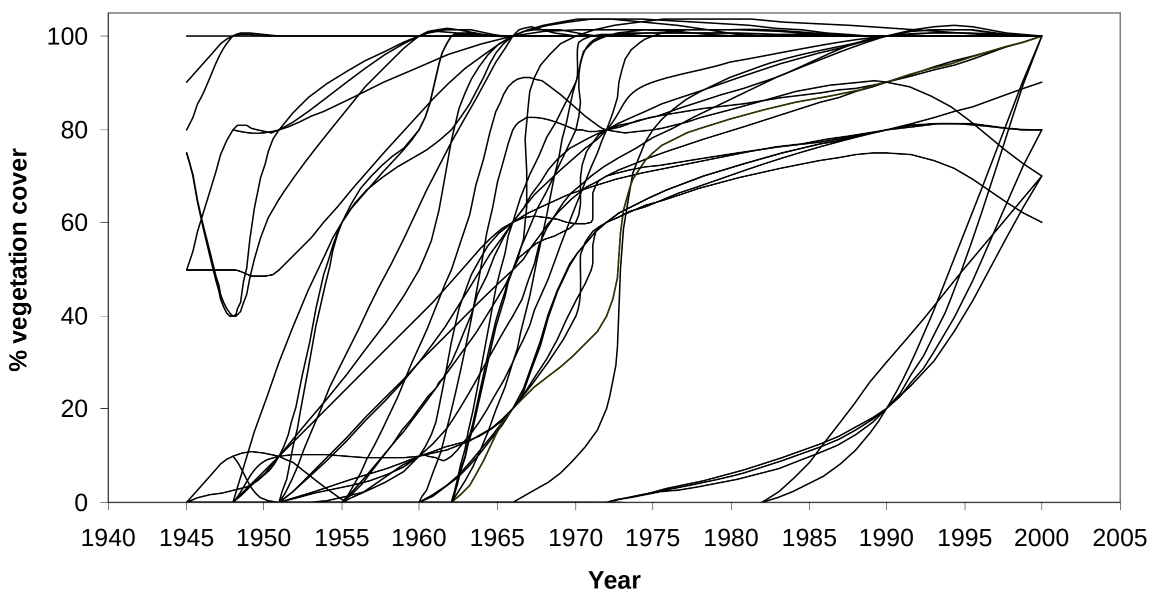


Figure 1. Curves showing progression of vegetation cover for each soil location.

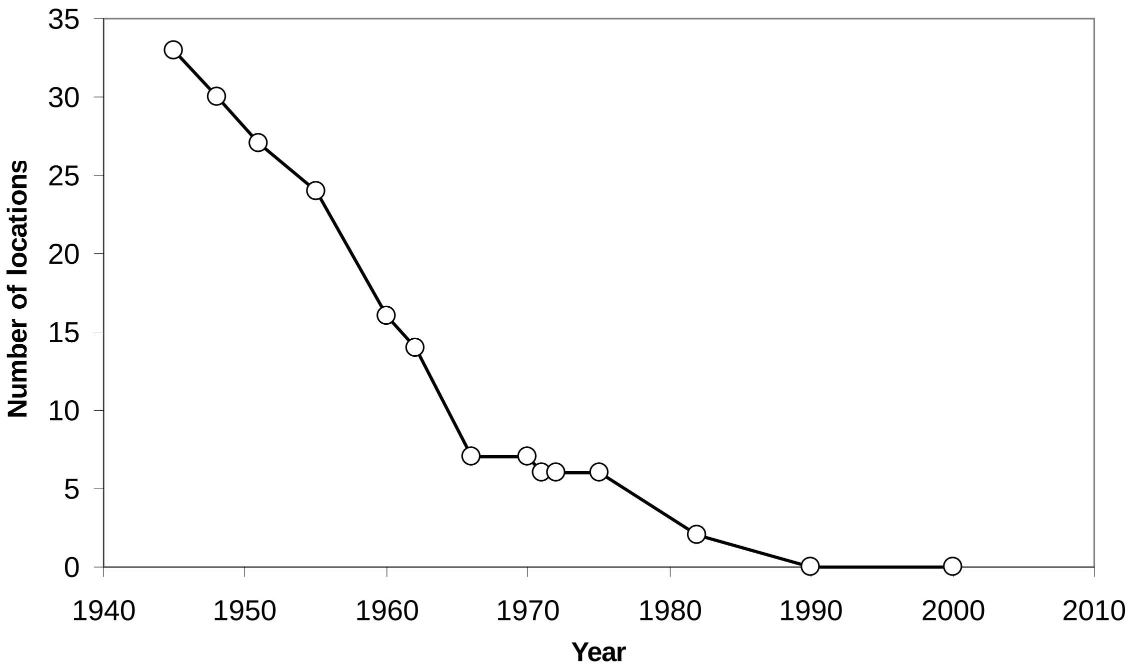


Figure 2 Number of locations at Newborough Warren with bare sand at each time point.

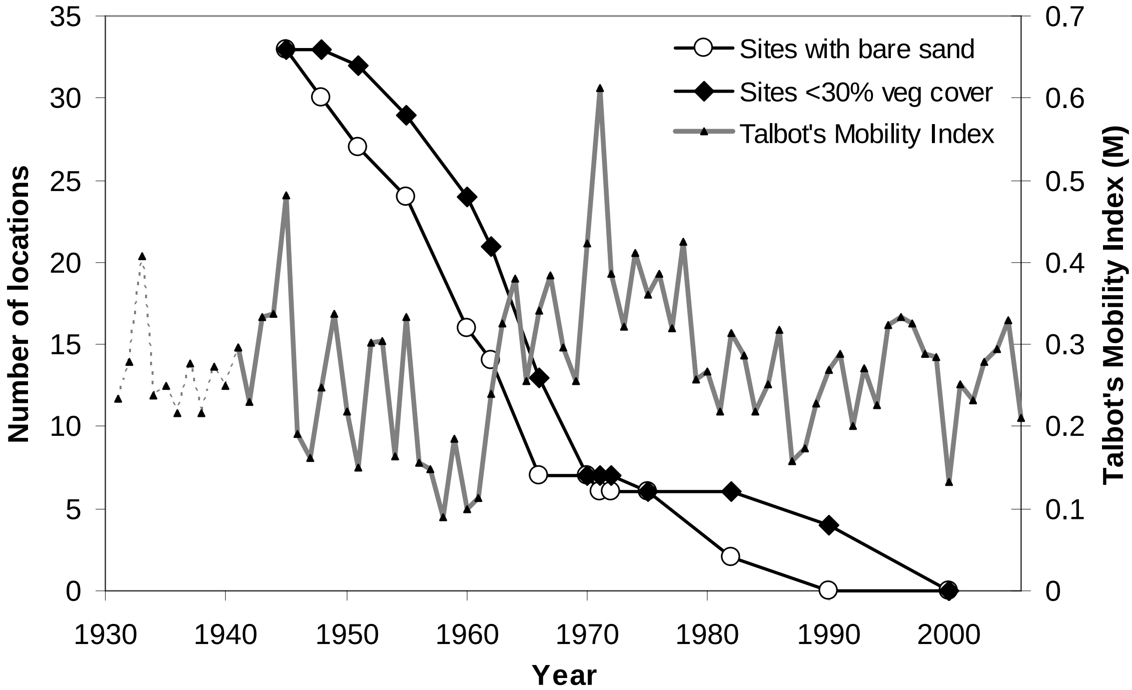


Figure 3 Number of locations with bare sand and with vegetation cover <30 % at each time point; overlain with Talbot's Mobility Index (M). Dotted line for M up to 1941 shows cruder calculation based on rainfall as no windspeed data were available. Meteorological data were obtained from RAF Valley.

A further possible cause of stabilisation may be afforestation on adjoining parts of the Warren. The first plantings occurred in 1949, although some stabilisation of the leading dune and bare sand surfaces to the north-west of the rock ridge also occurred around this time. While planting started in 1949, the initial plantings generally occurred on the more fertile hind dune areas, gradually moving towards the sea. Given the sequence of planting and the time taken for trees to reach a height sufficient to affect windspeeds, it is unlikely that afforestation was a main driver of stabilisation at Newborough, although it may be a contributing factor. Futhermore, the landforms in the open Warren are oriented with respect to the prevailing south-westerly winds suggesting that any effect of the forest on local windspeeds is probably limited to the area adjacent to the forest edge.

4.2 Rates of soil development at Newborough Warren

The calculated ages for each time point were plotted against measured soil parameters. The two parameters likely to be useful indicators of soil development and for which the most data were available were the organic matter content of the soil (measured as % Loss On Ignition – %LOI) and the thickness of the organic horizon, comprising F (Fermentation) and H (Humus) layers. This is often described as the organic or A horizon in previous studies. The relationships between these soil parameters and soil age will differ markedly between dry and wet dune habitats and are therefore discussed separately for the dry habitats (comprising mobile, semi-fixed and dune grasslands) and wet habitats (dune slacks and wet dune grassland). In the figures in this section, the data are plotted as age since first vegetated, and as age since fully fixed. Graphs for dry and wet habitats are shown on the same scale for comparison.

The data for each habitat type (dry or wet) are initially plotted against Loss on Ignition and against thickness of FH horizon. Although these both show similar trends, the %LOI data generally show less variability than the data for FH horizon thickness, particularly in the dry dune habitats. Various contributory factors to the greater variability in the FH horizon data may include the subjectivity of deciding where the FH horizon ends and the mineral horizon begins, particularly where organic material has moved down through the soil profile as a result of bio-turbation by earthworms for example, or when there is staining of the mineral soil by leaching of humic acids. Other factors contributing to disparities between the data on Loss on Ignition and thickness of FH horizons include situations where increased sand blow has buried a soil layer rapidly (resulting in a discrete buried soil layer whose nutrients are still available to plants) or slowly enough for vegetation growth and hence soil development to keep pace, resulting in a diluted soil profile. Loss on ignition is likely to be a more robust measure of the organic matter content of the soil and hence the water holding capacity and nutrients available within the rooting zone of most plants. Therefore, subsequent interpretation and analysis will focus on the %LOI data.

4.3 Soil development profiles at Newborough

4.3.1 Dry dune habitats

The data for the dry dune habitats are plotted as years since first vegetated (Figure 4) and as years since fully fixed (Figure 5), for %LOI and FH thickness (*a* and *b* for each pair of graphs). These data show that the %LOI data show a much tighter relationship with age than do the FH thickness data. The comparison of Figures 4 and 5 also suggests that in the dry dune habitats at least, accumulation of organic matter is relatively slow until vegetation cover reaches 100 %, and more rapid soil development occurs once full vegetation cover has been reached. This is summarised more simply in Figure 6, which separates soil development in samples that reached 100 % vegetation cover and those that did not. Although it may seem obvious that soil development progresses faster under full vegetation cover, it has implications for the management of dune systems, as it suggests that soil development can be retarded if these semi-fixed areas can be maintained in an open state.

The data in Figures 4a and 6 suggest a slow increase in organic matter content from a starting point of around 0.2 %LOI in the bare sand of mobile dunes to around 1 %LOI when vegetation cover reaches 100 %. This appears to take up to 40 years to reach this point, although the average time taken to become fully vegetated is 30 ±3.8 years in these dry dune habitats. There is then a steeper increase in the rate of soil development and, by 60 years after the onset of stabilisation, some soils have reached organic matter contents comparable to the much older soils. While we can not accurately age soils in this study older than 60 years, the estimated minimum ages of the older fixed grassland soils suggest that the organic matter content appears to level out, with values of around 3 – 4 %LOI in the oldest dune soils at this site. There is a lot of variability in this steeper part of the curve, with some soils only reaching organic matter contents of just over 1 %LOI by 60 years, while others reach over 3 %LOI by only 40 years. Uncertainty in the age estimates plays a part in this variability, but it is clear that other environmental factors have a large role in regulating the rate of soil development, and these are discussed in more detail in section 4.6 below.

It is interesting that the rate of soil development at Newborough appears to level off after 60 years. There are a number of possible reasons for this decrease. One is that once soil development and vegetation establishment have reached a certain level, then these habitats become viable for human utilisation which may slow the rate of soil development. There are many old field boundaries within the fixed dune grassland around the edges of the Warren, visible both from aerial photographs and the old OS maps. Historical evidence also suggests that large parts of what is now the Warren were used for agriculture in the past. Ranwell (1959) cites the large storm of 1331 which caused sand to blow over large areas of Newborough and led to 186 acres of land in the Warren becoming unfit for crofting. These areas were probably used for both livestock grazing and some arable cultivation. Aerial photographs from 1945 – 1960 show cultivated fields in parts of the Warren prior to planting with forest. Once land is used for grazing or cultivation, this generally slows down rates of soil accumulation. Grazing reduces the amount of carbon input to the soil *via* litter fall (Ritchie *et al.*, 1998), and may speed up soil mineralisation rates through the input of labile nitrogen as dung and urea (Pastor *et al.*, 1993; Ruess & McNaughton, 1987). Cultivation oxidises the soil and removes carbon both through increased microbial activity and through off-take in crops or mowing. Even if pasture and arable lands are improved by the addition of manure, the rate of carbon accumulation is slower than in an un-managed system.

A second reason is more intrinsic to development of a fully functioning soil system. In very young skeletal soils, the temperature extremes, variations in soil moisture and low structural complexity of the soil act to limit the range of soil organisms that can survive in these systems. As soil accumulation proceeds and the soil layer becomes thicker, the system becomes more buffered from physical factors. The deeper soil layers and increased availability of organic matter mean that a greater diversity of soil organisms can survive, including the full suite of decomposer guilds, thus increasing the rates of organic matter decomposition and transformation from dead plant material into soil.

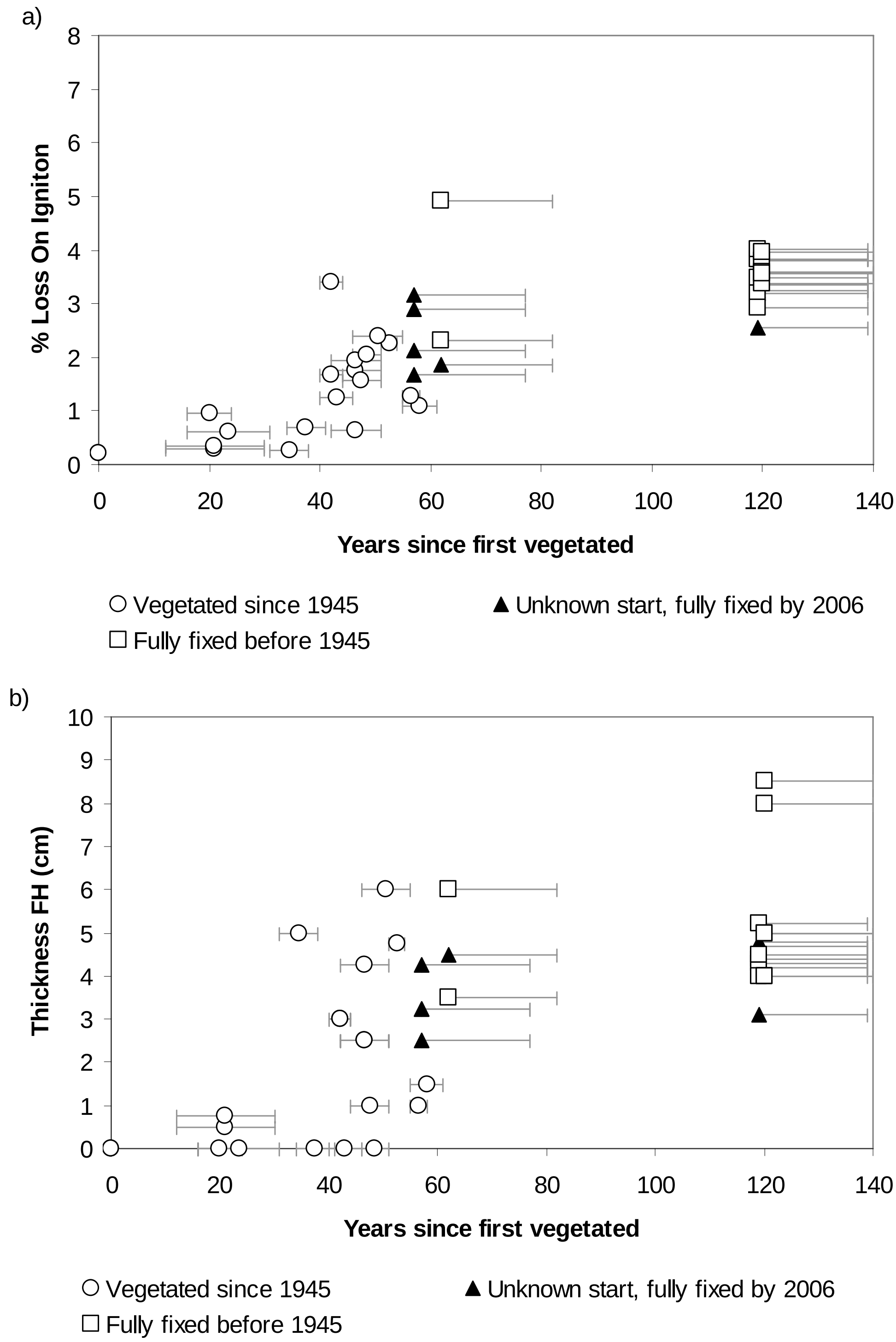
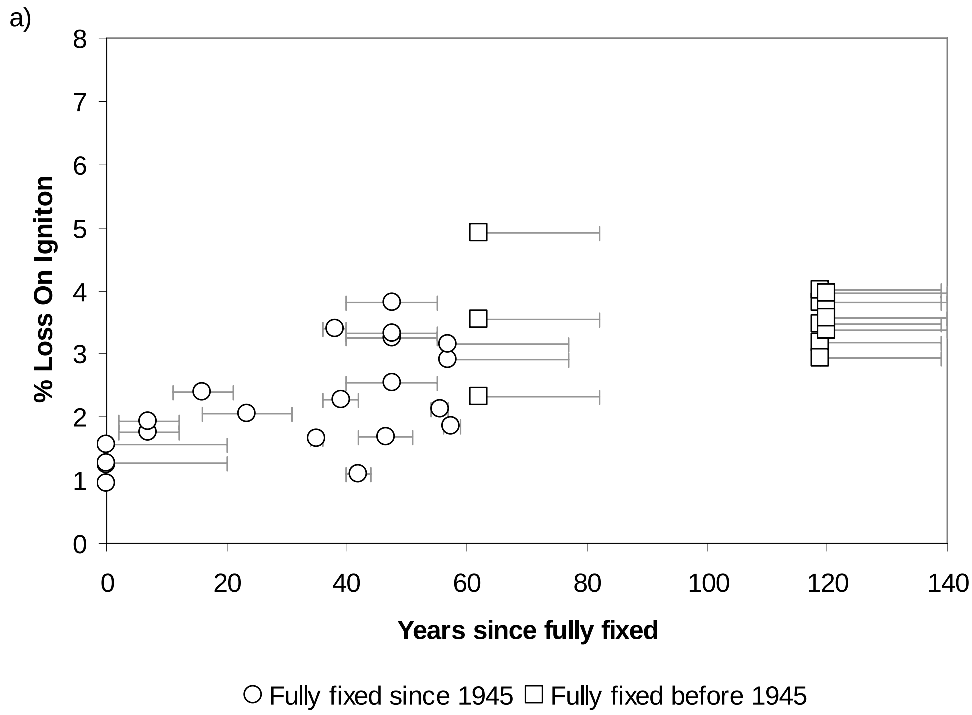


Figure 4. Dry habitats. Age of soil since locations were **first vegetated**, plotted against a) %Loss On Ignition and b) Thickness of the organic (FH) horizon. Open circles show locations where start date was known (i.e. since 1945); Filled triangles show locations where start date was unknown but for which the date at which they became fully fixed was known – here the minimum age is plotted; Open squares show samples which were fixed prior to 1945 – ages are estimated to be at least 120 years old (based on OS map of 1887, but are probably older). Equal error bars left and right of a data point show the likely potential age range. Unequal error bars denote large uncertainty and precise age is unknown.



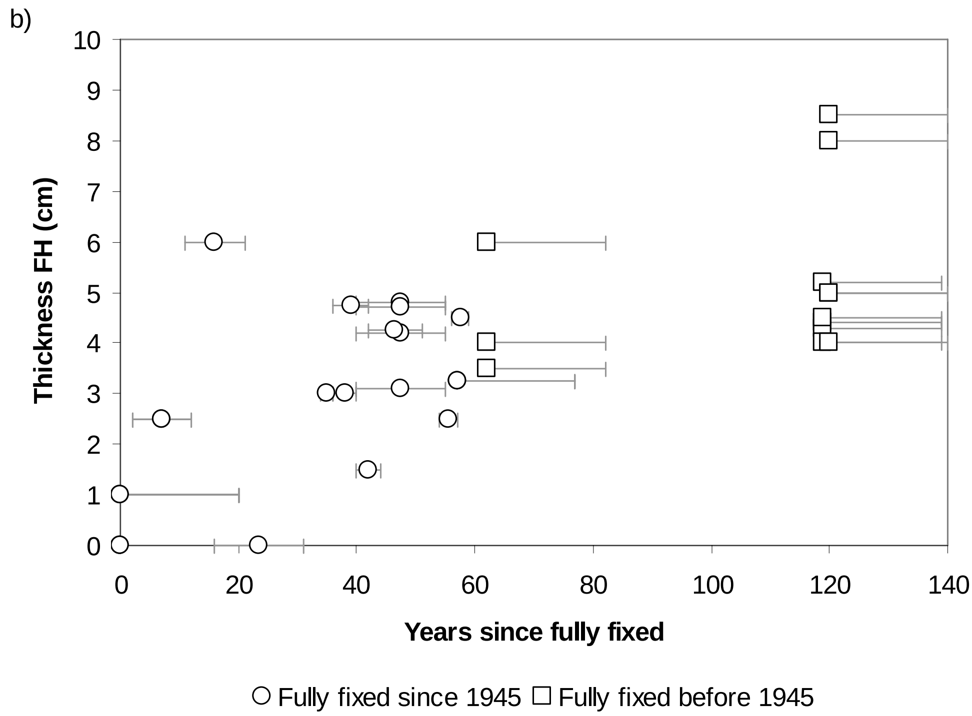


Figure 5. Dry habitats. Age of soil since locations were **fully fixed**, plotted against a) %Loss on Ignition and b) Thickness of the organic (FH) horizon. Open circles show locations fully fixed since 1945; Open squares show samples which were fixed prior to 1945 – ages are estimated to be at least 120 years old (based on OS map of 1887, but are probably older). Equal error bars left and right of a data point show maximum potential age range. Unequal error bars denote large uncertainty and precise age is unknown.

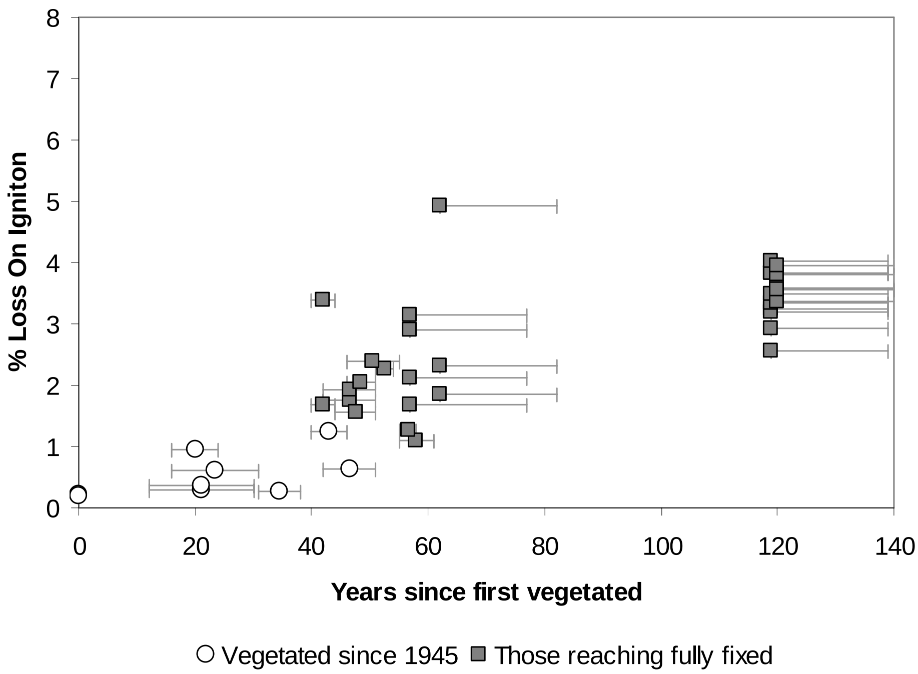


Figure 6. Dry habitats. Age of soil since locations were **first vegetated**, plotted against %Loss on Ignition. Open circles show locations first vegetated since 1945, but which did not reach 100 % vegetation cover; Grey squares show samples which have reached 100 % vegetation cover. Legend for error bars as per Figure 4.

A possible influence on organic matter supply may be extra N addition to the system as a result of biological N fixation. Legumes and N-fixing cyanobacteria are widespread in the early successional communities, but less common in the older fixed dune grassland, and this change in the quantity of N input to the system may also control rates of soil accumulation. This is discussed in more detail in section 4.7. Additionally, the balance of direct plant uptake of nitrogen and that mediated by microbial activity may also play a role. In soils in other habitats, ^{15}N tracer experiments have shown that most N deposition to the system is rapidly taken up by the microbial biomass before being subsequently released to the plant system (Nadelhoffer *et al.*, 1999). It may be that in these younger skeletal dune soils, a greater proportion of the N inputs to the system can be directly taken up by the plants, fuelling rapid biomass production and increasing the rate of organic matter accumulation in the early stages of soil development.

Lastly, it is possible that the shape of the curve is an artefact resulting from the ages assigned to the older soil samples. The filled triangles represent points which had incomplete vegetation cover in 1945, but which achieved full cover by 2006. The precise age for these points is therefore unknown but if we assume that similar rates of stabilisation by vegetation observed in this study apply to earlier time periods then their age lies between 60 and 100 years (from Figure 6, the maximum time to stabilisation is 40 years from the onset of vegetation establishment). These points are generally assumed to be younger than those represented by open squares which showed full vegetation cover in 1945 and which maps suggest may have been fixed grassland as long ago as 1850. These points could therefore be at least 150 years old and may well be older, but are aged as 119 years old based on the OS map of 1888. It should be noted that age estimates are based on the most reliable data sources. Therefore, locations at the edge of the Warren and locatable on the earlier OS maps have been given older ages, while points within the Warren may well be older than the estimates used here but we have no reliable age for them, so have been given younger ages by default. This applies particularly to the outlier at 60 years, with a %LOI of 4.9 which lies within the Warren fairly near to the sea. Other similar morphological features are clearly visible in the aerial photographs from 1945 and these may represent relicts of a well-established older soil layer. However, given that the estimated ages for these older soils are minimum ages, and that many of the soils are likely to be older, it is reasonable to assume the plateau effect is not an artefact and that the rate of soil development does decrease over time. One further consideration is whether the plateau is an artefact of sampling depth. However, in none of the soil cores did the organic horizon extend below the 15 cm sampling depth.

4.3.2 Wet dune habitats

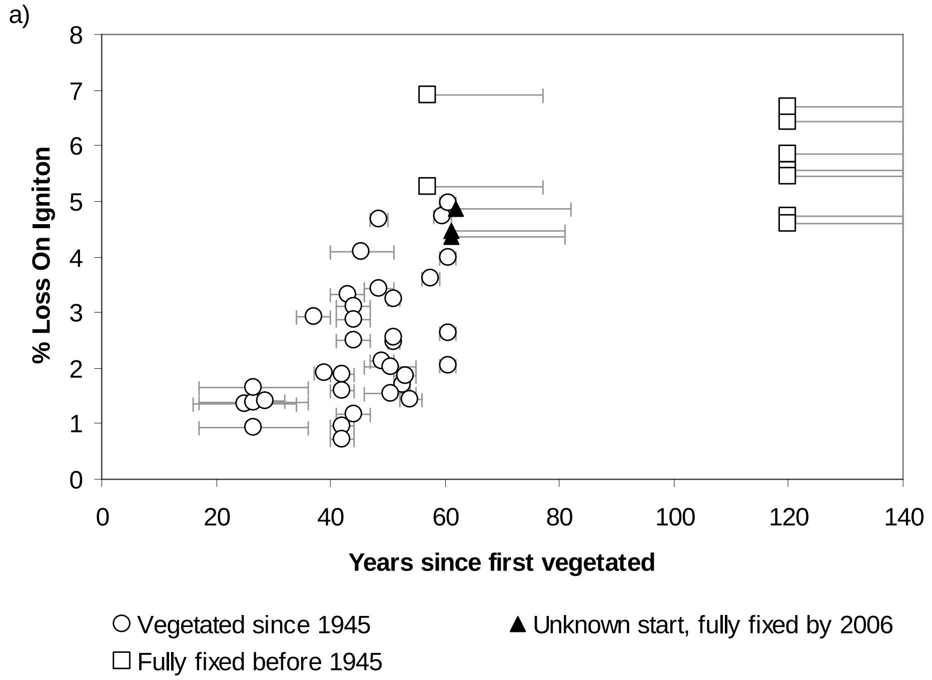
The data for the wet dune habitats are also plotted as years since first vegetated (Figure 7) and as years since fully fixed (Figure 8), for %LOI and FH thickness (*a* and *b* for each pair of graphs). The %LOI data and the FH horizon thickness data show a similar relationship, with a comparable degree of scatter. For consistency with the dry dune habitats, %LOI is used as the soil variable of interest in subsequent analyses.

It is readily apparent that the rate of soil development in the wet habitats is both faster, and reaches higher levels of organic matter. Analysis of the time profiles shows that dune slacks take on average only 12 ± 1.6 years to become fully vegetated, which is less than half the time taken by the dry dune soils. Some soils under 60 years old reach values of 4 – 5 %LOI and, as with the dry dune habitats, there is considerable scatter around the steeper part of the curve. The older soils once again appear to plateau out, this time at the higher level of 5 – 7 %LOI. However, there are few dune slack soils older than 60 years in the data, and the few examples where we can reliably assign an age greater than 60 years come from damp dune grassland within the Hewett plots. Therefore, these samples may not accurately represent the potential organic matter contents of older slack soils. Establishing reliable ages for the older dune slack soils would considerably improve the resolution of the older part of the curve.

4.4 Newborough data in the context of other studies

4.4.1 Dry dune habitats

A number of other studies have plotted rates of soil development in dry dune habitats with time. There are several comprehensive studies in the UK (Salisbury, 1922, 1925; Wilson, 1960) and in the Netherlands (Gerlach *et al.*, 1994). Figure 9 compares rates of organic matter accumulation in dune grasslands in the UK and Figure 10 shows a comparison with a Dutch study, with the Newborough data converted to the same units of kg N ha^{-1}. In the UK comparison, some points from the original studies also included samples under different vegetation types, including forest and dune heath. These have been excluded from Figure 9 to achieve a like-for-like comparison for dune grasslands since the vegetation type also plays a major role in rates of soil development. Figure 9 shows that the drier dune systems South Haven (Studland) and Blakeney show broadly similar rates of soil development, and these are much slower than the two wetter dune systems Southport and Newborough. The link with climate is also illustrated by Figure 10 where the Newborough soils appear to develop much faster than the Dutch soils at Spiekeroog, and reach levels of N pool comparable to much older soils with *Empetrum* heath, *Hippophae* or even forest cover. The most comparable dune



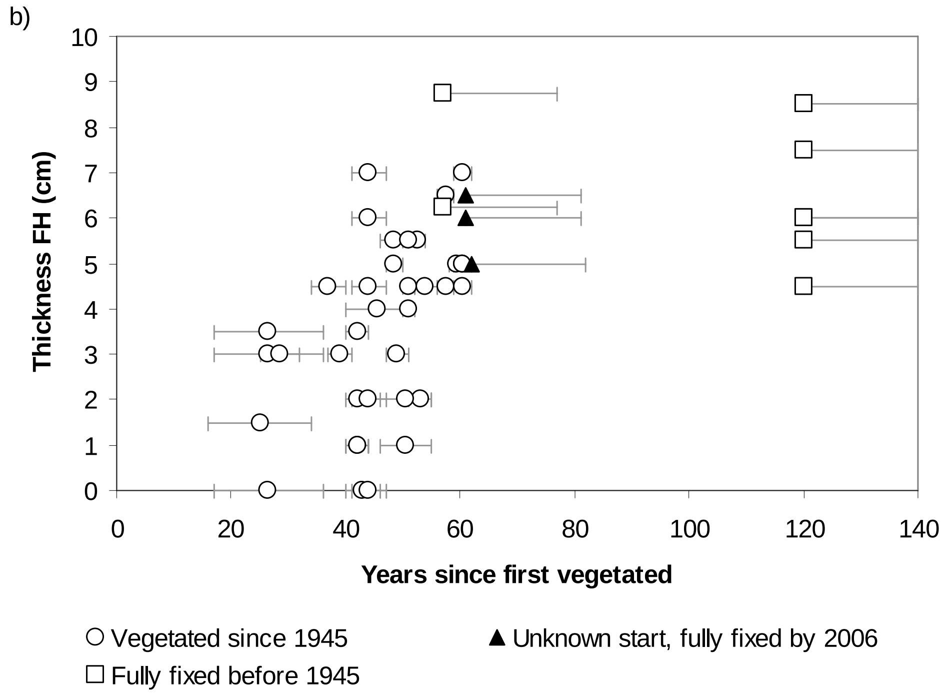
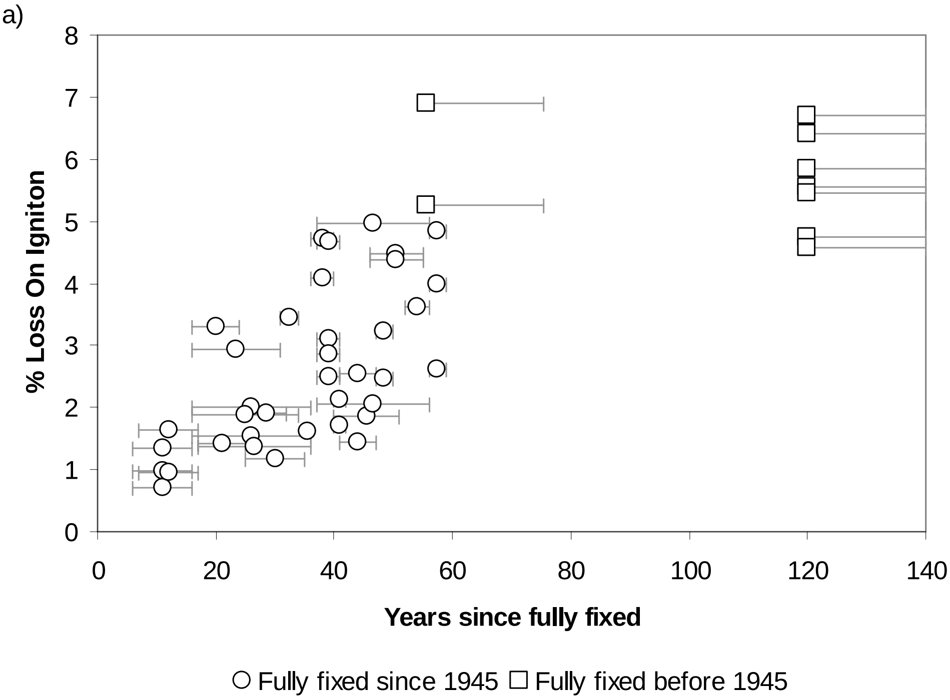


Figure 7. Wet habitats. Age of soil since locations were **first vegetated**, plotted against a) %Loss On Ignition and b) Thickness of the organic (FH) horizon. Open circles show locations where start date was known (i.e. since 1945); Filled triangles show locations where start date was unknown but for which the date at which they became fully fixed was known – here the minimum age is plotted; Open squares show samples which were fixed prior to 1945 – ages are estimated to be at least 120 years old (based on OS map of 1887, but are probably older). Equal error bars left and right of a data point show the likely potential age range. Unequal error bars denote large uncertainty and precise age is unknown.

a)



b)

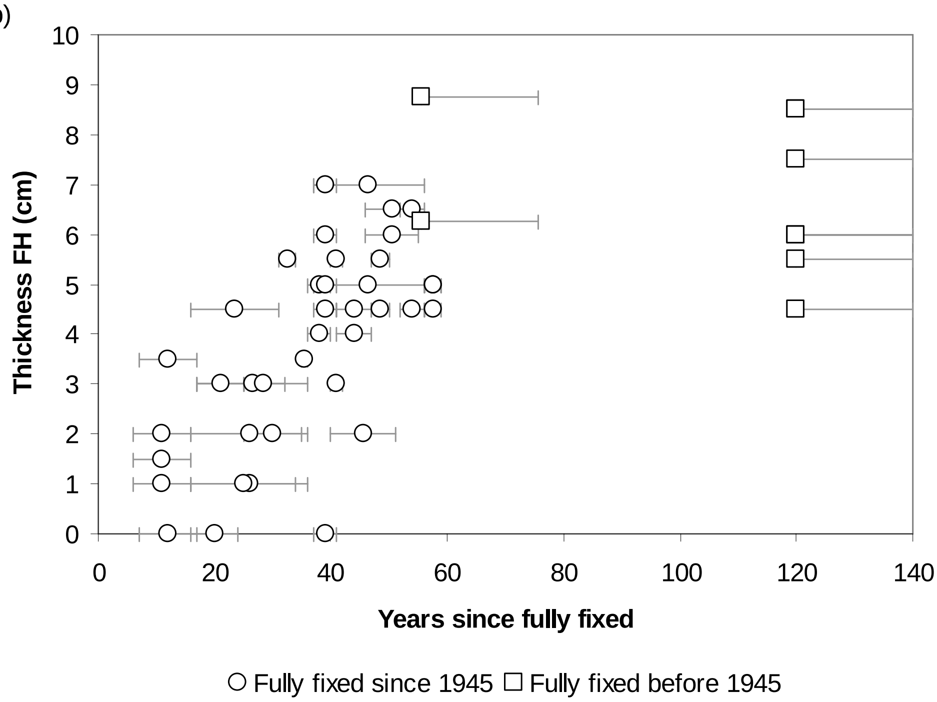


Figure 8. Wet habitats. Age of soil since locations were **fully fixed**, plotted against a) %Loss on Ignition and b) Thickness of the organic (FH) horizon. Open circles show locations fully fixed since 1945; Open squares show samples which were fixed prior to 1945 – ages are estimated to be at least 120 years old (based on OS map of 1887, but are probably older). Equal error bars left and right of a data point show maximum potential age range. Unequal error bars denote large uncertainty and precise age is unknown.

system to Newborough, Southport, shows a similar rate of soil development in the early stages of soil development, and the plateau in soil development for older soils observed at Newborough also applies at Southport. The range of %LOI values observed at Newborough encompasses those observed at Southport for soils estimated at 200 – 300 years old. However, one major difference emerges between the two dune systems for soils in the age range 40 – 60 years, where the Newborough values appear to show greater organic matter contents than the curve for Southport. Unfortunately, the limited data for Southport within this age range make direct comparison difficult. Reasons for these differences may include lack of similar age soil data for Southport, different habitats surveyed (the Newborough data may include some damper grasslands than the dry dune ridges sampled at Southport). There may also be fundamental differences driving rates of soil development at the two dune systems, although with similar climates and $CaCO_3$ contents of the sand parent material (Ranwell, 1959; Salisbury, 1925), it is difficult to immediately suggest what these may be. It is possible that a combination of climatic factors and N deposition may play a part as the Southport soils were sampled prior to 1925 and so may have experienced different conditions during their development than the more recently developed Newborough soils.

4.4.2 Wet dune habitats

There are no other data that we are aware of reporting rates of soil development for dune slacks in the UK, and the few published studies are from the Netherlands. Figures 11 and 12 compare Newborough data with Dutch data for organic matter pool and thickness of the FH horizon, respectively. In contrast to the dry dune habitats, soil development in the Dutch dune slacks is much more rapid than at Newborough. However, there is a likely reason for this. The Dutch chronosequences are based on recovery from turf stripping or sod cutting episodes, which leave the underlying mineral soil both in a partially decalcified state and with a residual organic matter content - the mineral sand at Terschelling in the youngest aged slack contains organic matter contents of 1.6 kg m^{-2} (Berendse *et al.*, 1998), almost double the levels found in mobile dune sand at Merthyr Mawr in S. Wales (Jones MLM, unpublished data). Both these factors promote rapid organic matter accumulation. The Dutch data also suggest that rates of soil development in dune slacks also level off with time.

4.5 Merthyr Mawr results in the context of the Newborough data.

The aerial photographs from 1948 for Merthyr Mawr show slightly less mobile sand than at Newborough, although this has not been quantified, and the mobile sand is often on steeper slopes against the escarpment. While limited dates were available for the Merthyr Mawr soil samples, they allow a comparison with the Newborough data. The Merthyr Mawr dates represent maximum ages due to the low temporal resolution between aerial photographs, however the points fall comfortably within the ranges observed at Newborough for both the dry dune and wet dune habitats (Figure 13). Newborough and Merthyr Mawr have broadly similar climate (Merthyr Mawr has slightly higher rainfall) and sand mineralogy. Therefore the similarity between these data suggest that conditions affecting soil development over this period have been comparable at both sites, and that these are large-scale influences rather than more local site-specific influences such as the planting of forestry at Newborough.

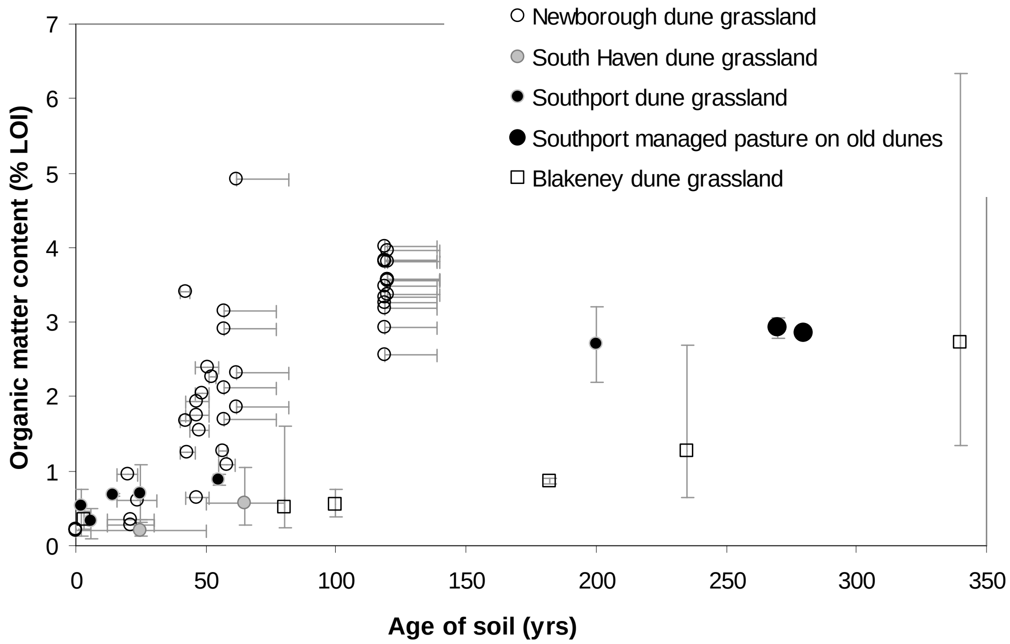


Figure 9. Plot of soil organic matter content (%LOI) against age in UK dune grasslands, for Newborough Warren, for South Haven – data from (Wilson, 1960), and for Southport and Blakeney – data recalculated from (Salisbury, 1922, 1925). Legend for x-axis error bars as per Figure 4. y-axis error bars denote range of values quoted in the literature.

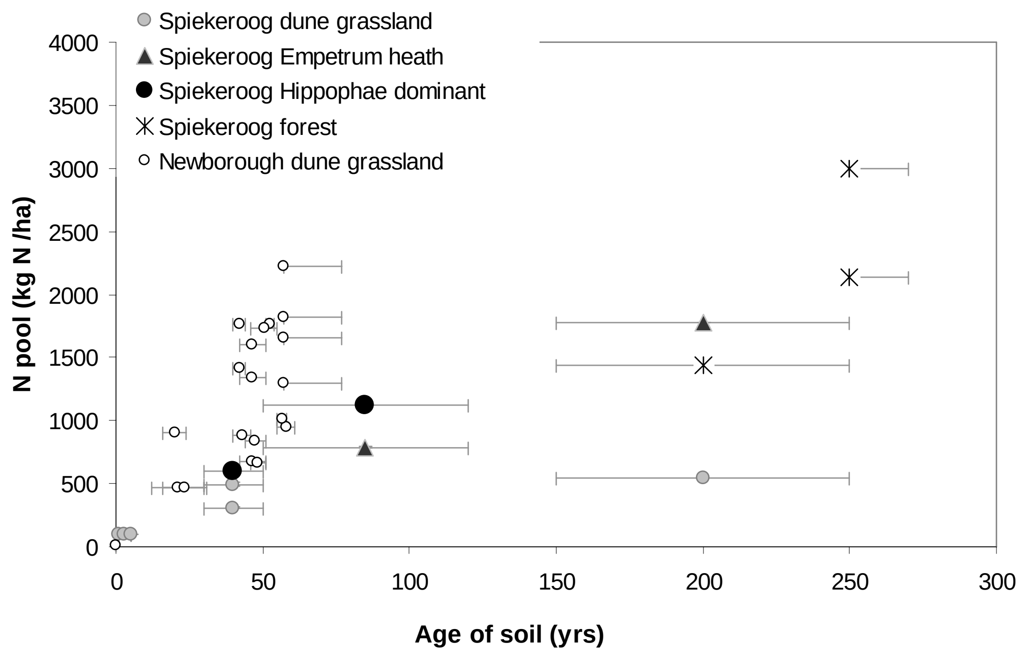


Figure 10. Plot of soil N pool (kg N/ha) against age for dune grasslands at Newborough Warren and for Spiekeroog in the Netherlands – data from (Gerlach *et al.*, 1994). Legend for x-axis error bars as per Figure 4.

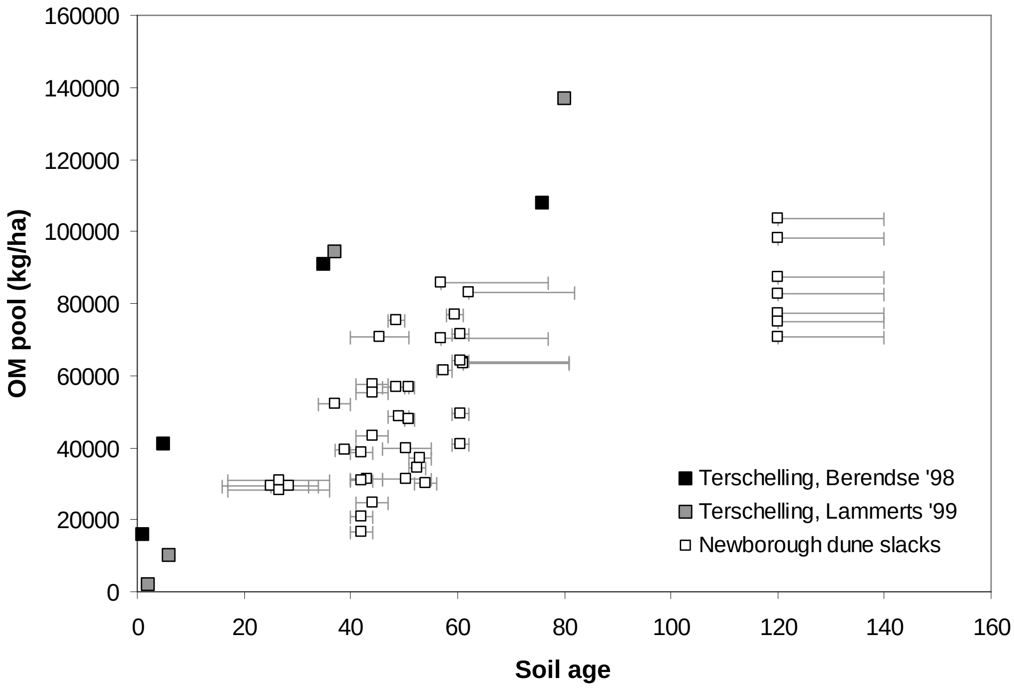


Figure 11. Plot of organic matter pool (kg OM/ha) against age for dune slack soils at Newborough Warren and for sod-cutting chronosequences at Terschelling in the Netherlands – data from (Berendse *et al.*, 1998; Lammerts *et al.*, 1999). Legend for x-axis error bars as per Figure 4.

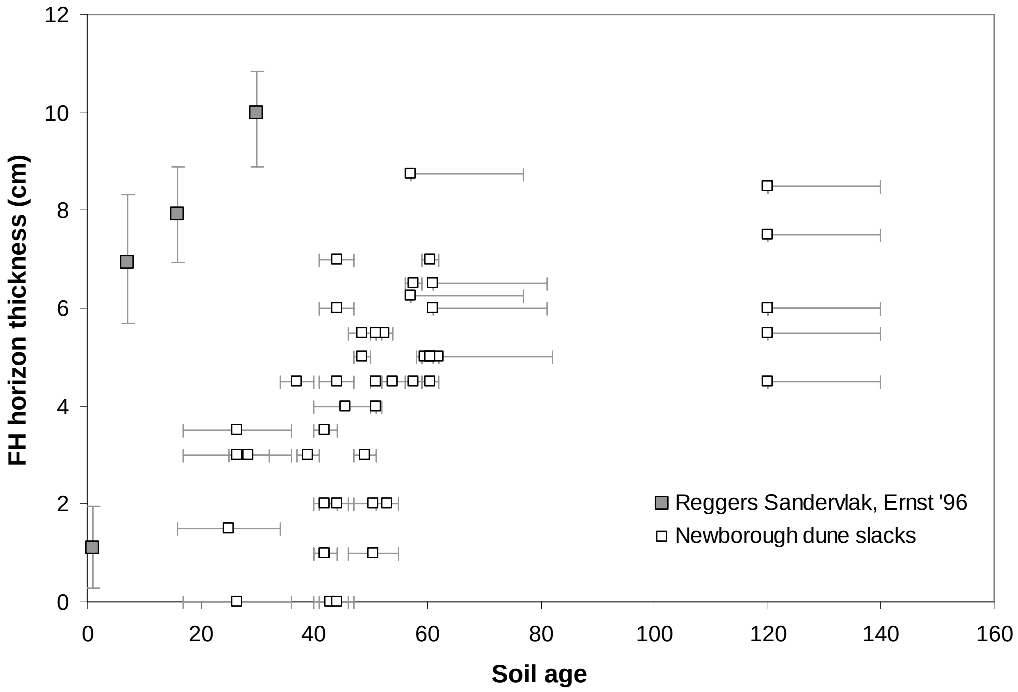


Figure 12. Plot of FH horizon thickness (cm) against age for dune slack soils at Newborough Warren and for a sod-cutting chronosequence at Reggers Sanderlak in the Netherlands – data from (Ernst *et al.*, 1996). Legend for x-axis error bars as per Figure 4. y-axis error bars show range of reported values.

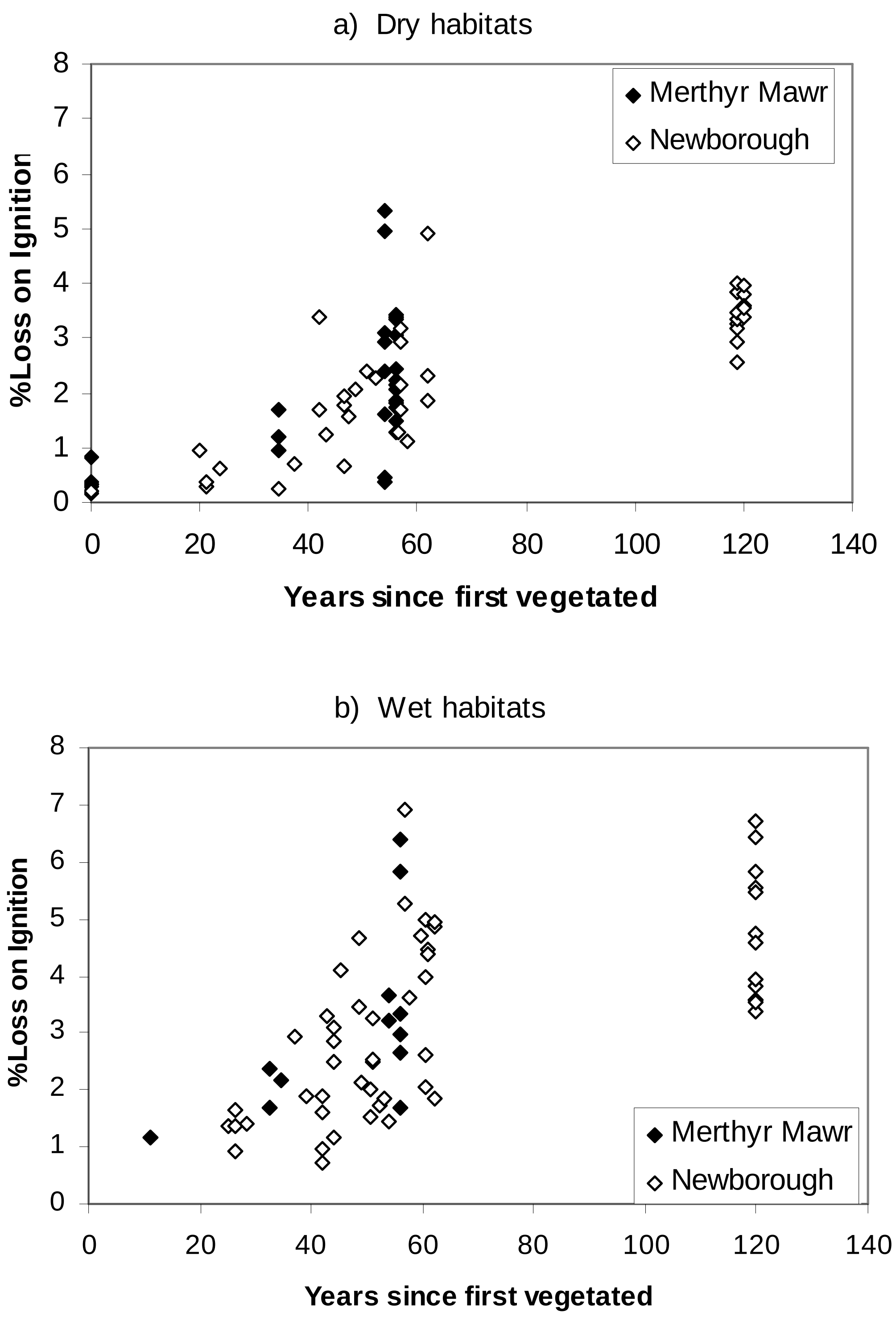


Figure 13. Comparison of soil organic matter contents plotted against age at Newborough Warren (open diamonds) and Merthyr Mawr (filled diamonds) for a) Dry dune habitats and b) Wet dune habitats.

4.6 Factors affecting the rates of soil development in the first 60 years.

The high variability around the steep part of the curve for both dry and wet dune soils at Newborough suggests that, even at one site, rates of soil development can vary considerably. This is reinforced by the differing rates of soil development at other studies in the literature, both in the UK and at sites in the Netherlands. In order to assess some of the factors contributing to this variability, a subset of the data for which we have accurate starting ages was analysed for the effects of climate, atmospheric N deposition, distance from the sea, disturbance, slope, aspect and topography with respect to height above the water table. Also discussed are the possible effects of vegetation type and management by grazing.

4.6.1 Climate, N deposition, and physico-chemical factors.

A subset of the data was prepared, for which the starting date of vegetation establishment was known. This dataset focuses on the first 60 years of soil development, and %LOI data were expressed as %LOI accumulation per year, in order to compare rates of soil accumulation for each data point over time. Climate records for RAF Valley were obtained going back to 1941, and the following annual climate variables were assessed: Average rainfall; combined summer rainfall for June, July and August; combined winter rainfall for December, January and February; average air temperature; average minimum temperature; average maximum temperature; number of frost days; average windspeed (missing data prior to 1986 were estimated using a regression relationship with number of gale days, so there will be a high degree of auto-correlation between these two variables); number of gale days; maximum gust; and Talbot's climatic Mobility Index (M). Annual atmospheric N deposition was reconstructed back to 1941 (Figure 14), using a generic historical reconstruction profile of NH_y and NO_x deposition for the UK (Fowler *et al.*, 2004), but parameterised for the oxidised and reduced N deposition at Newborough Warren in 1999 from Mohd-Said (1999) and internal CEH data. While trends for the UK predict deposition to decrease, subsequent measurements of ammonia concentration at Newborough (CEH, unpublished data) suggest a slight increase. Therefore, data beyond 1999 assume continuation of 1999 levels in the absence of detailed measurements. For each data point, climate variables and N deposition were averaged over the period of soil development for that location. Physico-chemical variables included: distance to the sea, soil pH measured in water and $CaCl_2$, and vegetation height. Distance to the sea was calculated using GIS and would have remained largely constant over the period of soil development, give or take a few tens of metres. Soil pH and vegetation height were measured at the time of sampling and may have differed over time. The importance of each variable in explaining rates of organic matter accumulation was assessed using linear regression, separately for the dry and wet dune habitats.

In the dry dunes, only a few variables were significant in explaining the variation (Table 2). These were annual average rainfall and distance to the sea which showed a loose positive relationship with organic matter accumulation rates, while vegetation height showed a negative relationship (Figure 15). Each variable explained approximately 20 – 25 % of the variation. Increasing distance from the sea appears to favour more rapid soil development and, particularly within 150 m of the sea (Figure 15d), rates of soil development are very low, probably due to the frequent disturbance and salt spray. Although the **rate** of organic matter accumulation does not significantly change with age in the dry dunes ($R^2 = 0.4$ %, $p = 0.740$), the negative relationship between vegetation height and soil development rates may be an artefact arising from the fact that the soils with the highest N accumulation rates tend to be the older soils which are heavily rabbit grazed and have a very short turf. Conversely, the

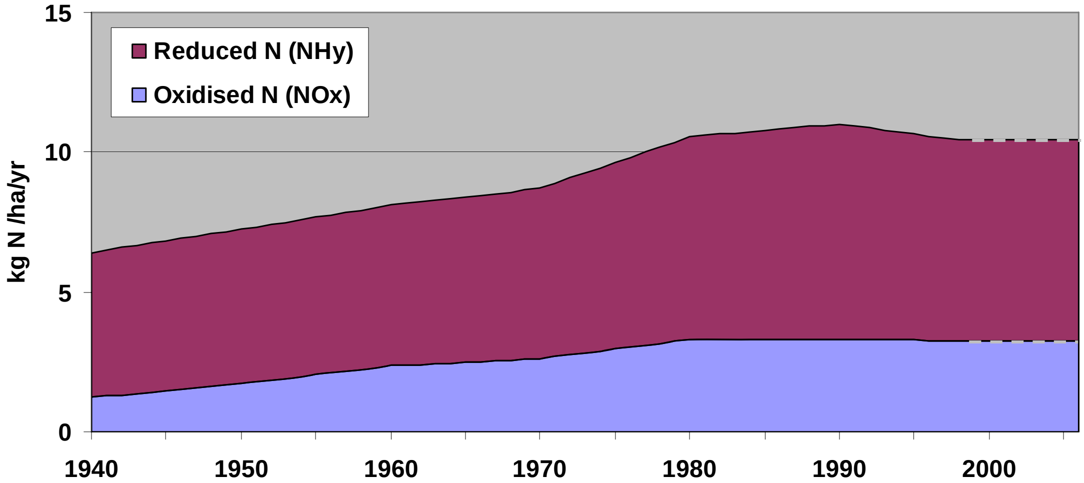


Figure 16. Reconstruction of combined oxidised and reduced N deposition at Newborough Warren, based on historical trends from Fowler et al. (2004), parameterised for Newborough using CEH data and from Mohd-Said (1999). Data beyond 1999 assume continuation of 1999 levels.

locations with tall vegetation are usually the semi-fixed grasslands near the sea with some A*mmophila* cover and whose soils have not yet started to rapidly accumulate. Nitrogen deposition on its own did not significantly explain much of the variation. When average rainfall and distance to the sea were combined in a multiple regression, they explained 39.2 % of the variation ($F = 5.48$, $p = 0.015$). Although the relationships are weak (Figure 15), they indicate that soil development is faster in cooler and in wetter periods in these dry dune habitats. This could either reflect increases in supply of organic matter (i.e. that summer drought does not limit vegetation growth), or decreases in decomposition rates in cooler, wetter years.

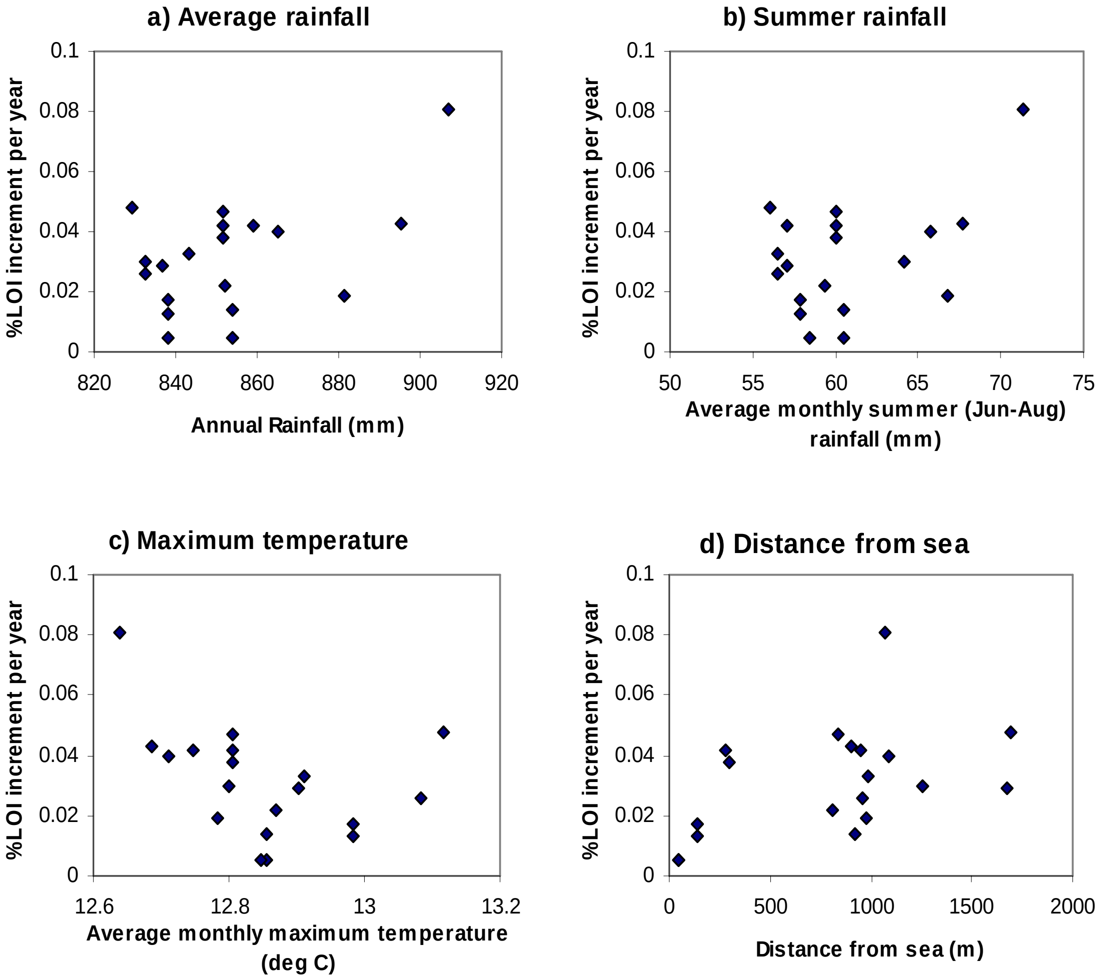
In the wet dunes, organic matter accumulation rate was not confounded with soil age (R^2 = 0.6 %, $p = 0.604$). Three closely linked variables related to temperature explained a significant proportion of the variation, when analysed individually by regression, as did soil pH (in water or $CaCl_2$) and vegetation height (Table 3). The relationship with temperature was negative and was strongest for minimum temperature (Figure 16b). The relationship with soil pH was also negative and strongest for pH measured in water (Figure 16f), while there was a positive relationship with vegetation height (Figure 16e). The data again suggest that soil development is more rapid in cooler periods. In cooler years, microbial decomposition would be generally slower and, since vegetation growth in dune slacks is less likely to be moisture limited than in the dry dunes, this suggests that soil accumulation in dune slacks is driven primarily by controls on decomposition rather than controls on carbon production. However, the strong negative relationship with soil pH suggests that supply of plant material may also play a role. While decomposition rates tend to decrease at lower soil pH this only occurs below a pH of around 5. However, as soils become less base rich, decreasing from ph 8 down to around pH 6 -7, availability of iron and phosphorus increases (Kooijman *et al.*, 1998; Kooijman & Besse, 2002) which may stimulate plant productivity. The relationship

Table 2. Significance of a range of environmental variables in explaining accumulation rates of soil organic matter in **dry dune habitats**. Those in bold are significant at $p < 0.05$, those in bold italics are significant at $p < 0.10$.

	regression coefficient	R^2	F	p
N deposition	-0.0055	9.8	1.84	0.193
Rain	**0.0004**	**25.7**	**5.88**	**0.027**
Summer rain	***0.0019***	***19.9***	***4.22***	***0.056***
Winter rain	-0.0013	2.6	0.45	0.513
Ave temp	-0.039	13.8	2.72	0.117
Min temp	-0.0262	8.2	1.53	0.233
Max temp	***-0.059***	***16.5***	***3.36***	***0.084***
Frost days	0.0014	3.4	0.6	0.449
Wind speed	0.0035	4.5	0.8	0.384
Gale days	0.0014	9.9	1.86	0.19
Max gust	0.0004	3.6	0.64	0.436
Mobility index	0.15	9.1	1.71	0.208
Sea distance	**0.00002**	**22.8**	**5.03**	**0.039**
pH (water)	0.0094	1.3	0.24	0.632
pH ($CaCl_2$)	0.0020	0.7	0.15	0.707
Veg height	**-0.0004**	**23.1**	**5.41**	**0.032**

Table 3. Significance of a range of environmental variables in explaining accumulation rates of soil organic matter in **wet dune habitats**. Those in bold are significant at $p < 0.05$.

	regression coefficient	R^2	F	p
N deposition	-0.004	3.9	1.38	0.247
Rain	0.00002	0.2	0.05	0.819
Summer rain	0.0002	0.8	0.27	0.61
Winter rain	-0.0004	1.2	0.43	0.519
Ave temp	**-0.042**	**12.7**	**4.94**	**0.033**
Min temp	**-0.065**	**17.8**	**7.35**	**0.01**
Max temp	-0.025	5.3	1.91	0.176
Frost days	**0.002**	**11.9**	**4.59**	**0.039**
Wind speed	0.002	0.9	0.29	0.592
Gale days	0.0001	0.2	0.05	0.82
Max gust	-0.0001	1.9	0.65	0.425
Mobility index	0.013	0.2	0.06	0.811
Sea distance	0.00001	5.4	1.96	0.171
pH (water)	**-0.0293**	**35.2**	**9.22**	**0.007**
pH ($CaCl_2$)	**-0.03939**	**21.6**	**4.68**	**0.045**
Veg height	**0.0019**	**30.1**	**7.33**	**0.015**



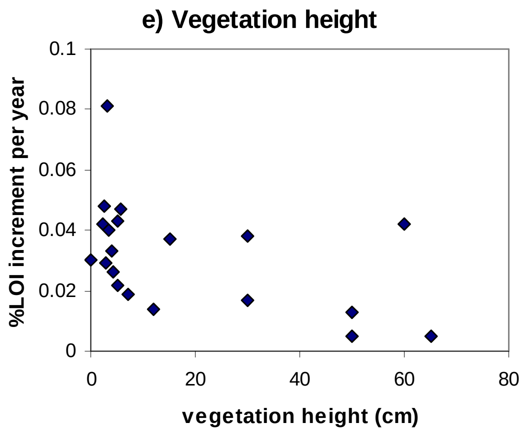


Figure 15. Rates of organic matter accumulation in **dry dunes** at each location plotted against selected environmental variables averaged over the time period of soil accumulation at that location, showing: a) Annual rainfall, b) Summer (Jun - Aug) rainfall, c) Monthly maximum temperature, d) Distance from the sea, and e) Vegetation height.

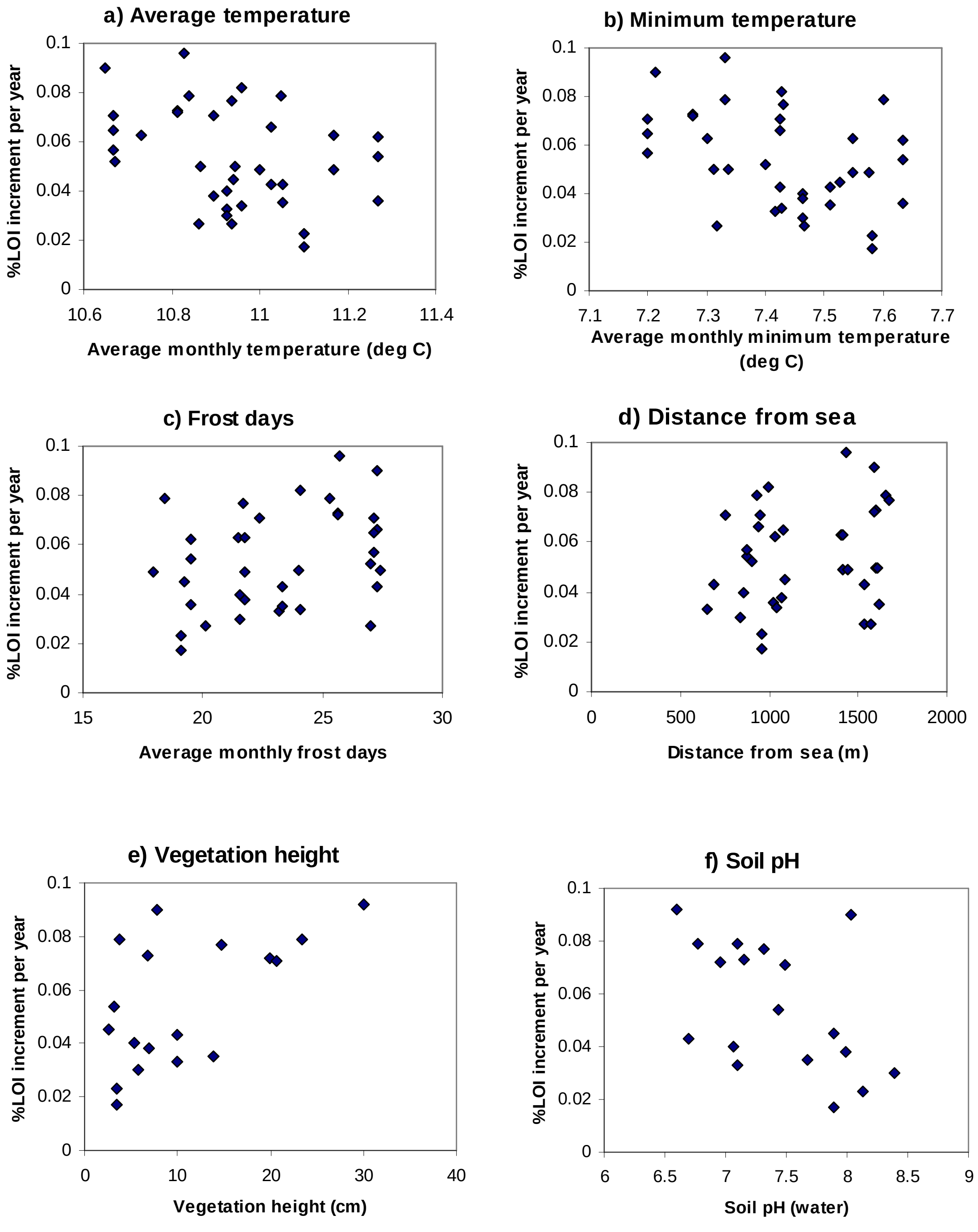


Figure 16. Rates of organic matter accumulation in **wet dunes** at each location plotted against selected environmental variables averaged over the time period of soil accumulation at that location, showing: a) Average temperature, b) Minimum temperature, c) Number of frost days, d) Distance from the sea, e) Vegetation height and f) Soil pH (measured in water).

with vegetation height may be ecologically meaningful in the dune slacks. While there is considerable variation in vegetation height for soils with a high LOI accumulation rate, organic matter in the less heavily grazed dune slacks (represented by greater sward heights) might be expected to accumulate faster due to increased supply of plant material in litter fall. Neither distance to the sea (Figure 16d) nor N deposition explained any significant amount of the variation.

Interestingly, while Talbot's Mobility Index provides some interpretation on rates of dune stabilisation by vegetation, once the vegetation is stabilised the climatic conditions as summarised by the Mobility Index, which is strongly driven by wind speed, seem to have little bearing on subsequent rates of soil development in either the dry or the wet habitats.

4.6.2 Disturbance

The effects of disturbance have partly been discussed with respect to distance from the sea, above. Disturbance undoubtedly plays a large part in affecting rates of organic matter accumulation, whether through burial by blowing sand, or disturbance by animals or blow-outs. Disturbance acts to return soil development to an early stage and is one reason for the large ranges in %LOI rates reported by Wilson (1960) and Salisbury (1922), who both quote very low %LOI values in disturbed areas of dunes aged at hundreds of years. Unfortunately, it is difficult to quantitatively assess the effects of disturbance. The closest analogue we have for climatic disturbance is Talbot's Mobility index, which did not significantly explain any of the variation in rates of soil development. If yearly rabbit population data were available for Newborough from 1945 onwards, that would enable statistical analysis of the likely effects of rabbit disturbance. However, these data are not available and we can only guess at the effects. While myxomatosis devastated the rabbit population at Newborough in 1955, and rapid vegetation change was observed in the following years (Ranwell, 1960), it is apparent from Figure 3 in section 4.1 above that vegetation stabilisation had commenced before the advent of myxomatosis, and coincides with a period of low values of Talbot's Mobility index, so it is difficult to reliably separate these effects. Therefore, while we know that disturbance is an important control on soil development, our ability to quantify its effects over time is limited.

4.6.3 Slope and aspect

A smaller subset of the data with only 22 points, was available for analysis of the effects of slope and aspect on rates of organic matter accumulation in dry dune habitats. Slope was divided into four classes of increasing steepness: Flat, 1 – 6 degrees, 7 – 14 degrees, and > 14 degrees. Aspect was also divided into four classes, with respect to the direction of the south-westerly prevailing winds: facing south west, north west, south east and north east. While analysis of variance showed that neither the effects of slope nor aspect were statistically significant, rates of organic matter accumulation (Figure 17a) tended to decrease on steeper slopes ($F = 1.05$, $p = 0.393$), and accumulation rates tended to be higher on north-west and south-east facing slopes and lowest on south-west and north-east facing slopes (Figure 17b; $F = 1.73$, $p = 0.189$).

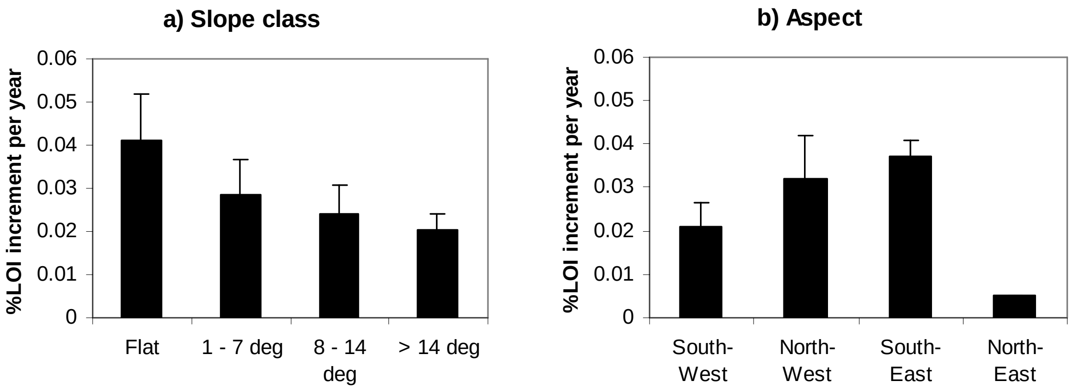


Figure 17. Effects of a) slope, and b) aspect, on rates of organic matter accumulation in dry dunes. Bars show ±1 s.e.

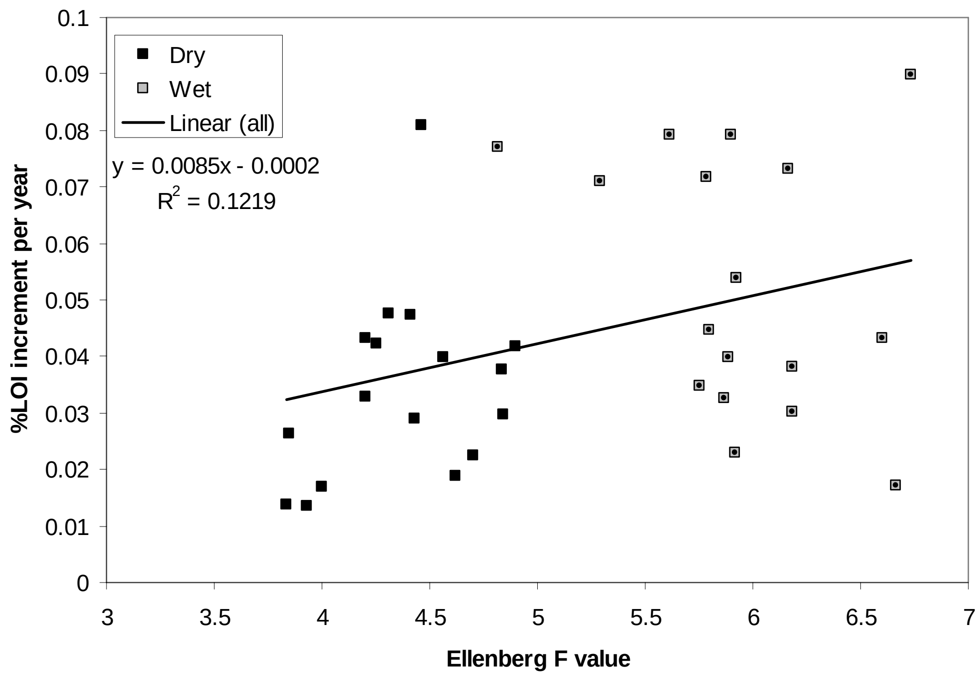


Figure 18. Plot of Ellenberg F (moisture) values against organic matter increment per year. Dry habitats (black squares) and wet habitats (grey squares) are separated, with a line of best fit applied to all points.

4.6.4 Soil moisture effects on soil development

Soil moisture controls both plant growth and soil biological activity. Wetter soils accumulate organic matter more quickly than drier soils, primarily due to slower rates of decomposition of plant material. Ellenberg F (moisture) values were used as an analogue for soil moisture conditions in this study and these values were available for a subset of 34 data points. Ellenberg F values are plotted against increment of organic matter in Figure 18. This shows that, as expected, wetter habitats have a faster rate of organic matter accumulation than drier habitats. However, soil moisture explains only 12 % of the observed variation and, particularly in the dune slacks there is high variability. Other environmental factors could account for this variation or, alternatively, Ellenberg F values may not be a suitable analogue for moisture conditions in wet slacks. This may be due to differences in the moisture requirements of the present day vegetation from that which was growing in the earlier stages of soil development, or it may be that Ellenberg F values do not accurately pick out small differences in the height of the water table which might exert a large control on rates of organic matter decomposition.

4.6.5 Vegetation type

Soil development is also controlled by the type of vegetation cover. This affects soils by altering the rate of input of senesced plant material, and by the litter quality which affects the rate of decomposition and N cycling (McClaugherty & Berg, 1987). Figure 19 shows rates of dune soil development under different types of vegetation cover reported in the literature. It is clear from this plot, and from Figure 10 presented earlier, that organic matter accumulation at a site is much greater in soils with heath or tree cover than under grassland; typically 4-5 times greater. The data available from soil samples taken as part of the Hill & Wallace study should in theory allow us to construct a similar curve for Newborough. However, although a similar shaped curve of soil development is produced, it became apparent that the data were not comparable since the older forested soils on fixed dune grassland should have similar or even greater organic matter contents to the same soils which had not been forested. Instead, they are considerably lower. The methodology for soil sampling differed between the studies. At each location, Hill & Wallace took a soil sample, approximately 5 cm diameter, sideways into the wall of a shallow soil pit at 5 cm depth (Hill & Wallace, 1987), whereas the CEH data were sampled to a standard depth of 15 cm. Therefore, as part of the limited additional fieldwork for this study, a calibration exercise was undertaken, where the two methodologies were compared, in paired samples at locations in the dune and forest, in younger soils towards the sea, and in older soils in previously fixed dune grassland. Due to time and access constraints, only two sets of samples were taken from the forested area, as the bulk of the field sampling had focused on increasing the resolution of ages within dune slacks, and the effects of grazing. Figure 20 shows the results from the inter-comparison. Unfortunately, there is no reliable way to correct the Hill & Wallace data so that it is comparable with the CEH data. In a thin soil, a sample at 5 cm depth is likely to underestimate LOI as measured by a 15 cm depth core, since it will largely miss the thin surface organic layer. Conversely, a core at 5 cm depth in a thick organic soil down to say 7 cm will overestimate LOI as it is not diluted by the mineral sand below it. The comparison was further complicated by the very high spatial heterogeneity in the samples even though paired soil samples were taken no more than 30 cm apart. Figure 21 shows the Hill & Wallace data plotted with the dune grassland data, and the two additional forest soil samples collected as part of this study, which give an indication of the likely effects of forest cover on dune soil development at Newborough.

4.6.6 Management, including natural grazing

Grazing is the most common form of management of fixed dunes, apart from control of trampling pressure by fences and boardwalks. As discussed in the introduction, grazing is likely to reduce rates of soil accumulation by reducing the input of organic matter and increasing the turnover of organic matter through increasing mineralisation rates. Grazing animals may remove some nitrogen and carbon from the system in live-weight gain, although these values are typically very low in unimproved pasture – usually in the order of 1 - 2 kg N ha^{-1} yr^{-1} (Perkins, 1978; Rawes & Heal, 1978). On the other hand, an experiment in a Dutch dune system showed that grazing served to reduce leaching losses of N (ten Harkel *et al.*, 1998), effectively increasing retention of N in the system. Most grazing management varies from year to year both in stocking densities and frequently also the type of stock. Separating out effects of grazing from other factors is very difficult, and designed experiments examining the effects of grazing are rare, particularly with regard to effects on soils.

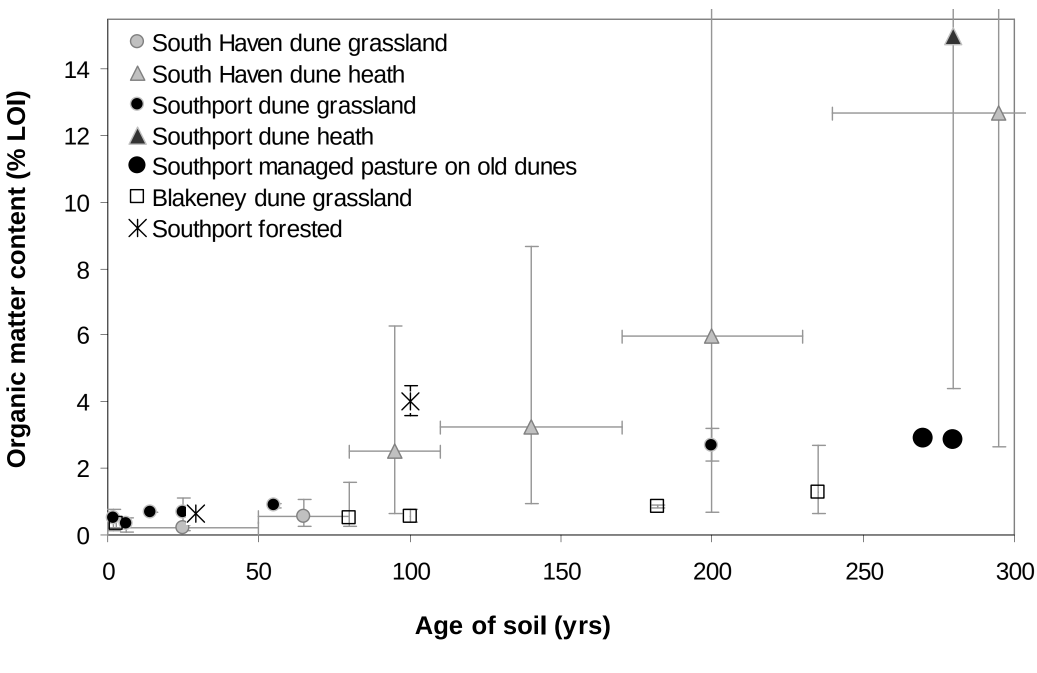


Figure 19. Soil profile development from the literature, under a range of vegetation cover types, including grassland, dune heath and forest. X-axis error bars show uncertainty in the age ranges. Y-axis error bars show the range of reported %LOI values.

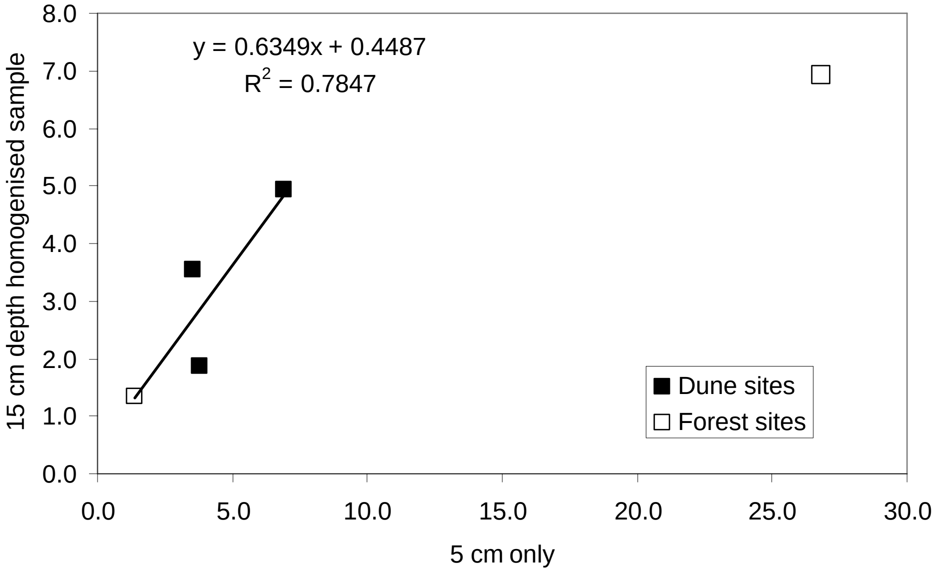


Figure 20. Calibration exercise to try and correct Hill & Wallace soil data collected at 5 cm depth to the CEH soil data sampled to 15 cm depth. Unfortunately, even ignoring the outlier in the top right of the diagram, applying this correction further reduces the %LOI values for the older soils in the Hill & Wallace data.

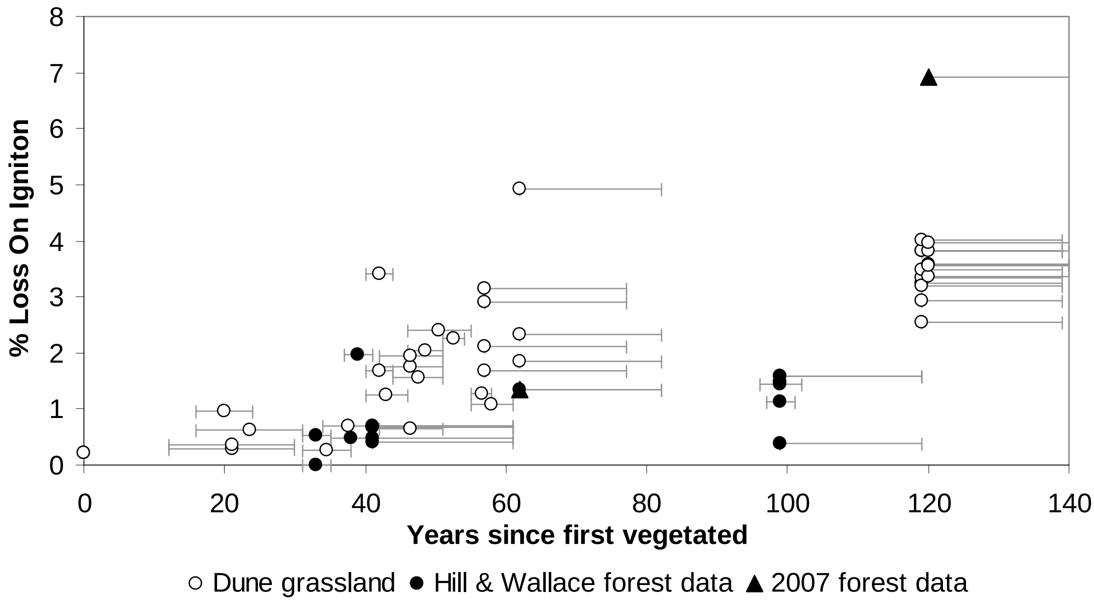


Figure 21. Comparison of dune grassland and forestry age profiles, showing that the Hill & Wallace data (black circles) are not directly comparable. The two black triangles show possible values for %LOI under forest in soil sampled to 15 cm depth.

David Hewett in ITE, a pre-cursor of CEH, set up in 1979 a complex replicated block grazing experiment using Soay sheep at Newborough (Hewett, 1982, 1985). This ran for approximately 20 years, before it was finally stopped in 2001 as a consequence of the foot-and-mouth outbreak. Some vegetation survey work is reported from this experiment (Hewett, 1985), but there is little other data on the long-term effects of the grazing treatments. In 2002, an MSc project on the vegetation and soil characteristics were conducted on these plots. However, the study analysed the organic and mineral horizons separately, which could not be re-combined for this study. Therefore, re-sampling the former grazing plots was part of the fieldwork in this study. As the water table was quite high on the day of field-sampling, it was possible to accurately compensate for soil moisture effects by sampling at a fixed height (approximately 20 cm) above the water table on the day. In addition, in the most heavily grazed treatment, the effect of soil moisture availability was compared by sampling from drier locations within each replicate paddock in addition to the routine samples collected. A subset of the grazing treatments were sampled, to give a gradient of increasing grazing pressure. These treatments were: Ungrazed, Summer (May – Aug) grazing with 4 sheep, Summer (May – Aug) grazing with 8 sheep, Year-round grazing with 4 sheep and Year-round grazing with 8 sheep. Figure 22 shows the %LOI in each treatment. The results are counter-intuitive; it was expected that after 20 years, increased grazing pressure would result in progressively lower %LOI, partly through compaction of the organic layer and hence greater inclusion of mineral sand in a 15 cm depth sample, and partly through reduced litter input and enhanced decomposition of existing organic matter. Instead, %LOI appears to increase with grazing pressure, although this is not statistically significant. Use of bulk density and moisture content as covariates did not affect the statistical outcome. The additional samples taken from drier locations put the differences between the grazing treatments into perspective. Within the same grazing paddocks, there is a greater difference in %LOI between drier and wetter locations, than across different grazing treatments. Thus, while grazing appears to have little effect on soil organic matter content, even over a 20-year period, the importance of topography and water availability effects is reinforced.

In addition to managed grazing, natural grazers could also potentially have an impact on rates of soil accumulation. Data from Merthyr Mawr comparing organic matter content in areas grazed by rabbits and areas which had been ungrazed for a period of at least 20 years are presented in Figure 23. Although not statistically significant for either the dry dune grasslands (ANOVA, $F = 4.52$, $p = 0.052$) or the dune slacks (ANOVA, $F = 3.30$, $p = 0.119$), organic matter content (%LOI) tends to be lower in rabbit grazed areas than in ungrazed. These data suggest that grazing slows the rate of soil organic matter accumulation, primarily by reducing the supply of organic material in the form of plant litter. The soil thickness in the dry dune sampling locations at Merthyr Mawr is 3 - 4 cm on average compared with 6.1 cm in the fixed dune grassland at Newborough where the Hewett grazing plots were situated, so it is likely that the Merthyr Mawr soils are much younger. It may be that differences in organic matter accumulation are only apparent in soils with a relatively small organic matter pool, and where these differences have built up over a long enough period of time.

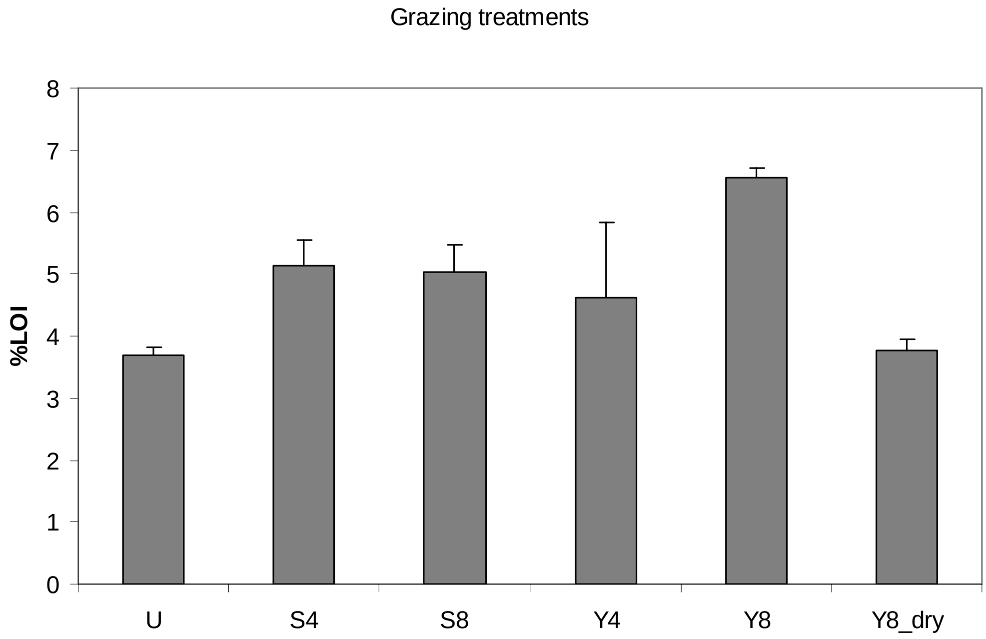


Figure 22. Organic matter content in a 20-year grazing study at Newborough. U - Ungrazed, S4 - Summer grazing with 4 sheep, S8 - Summer grazing with 8 sheep, Y4 - Year round grazing with 4 sheep, Y8 - Year round grazing with 8 sheep, Y8_dry - as Y8 but sampled from drier locations within the plot. Bars show ±1 s.e.

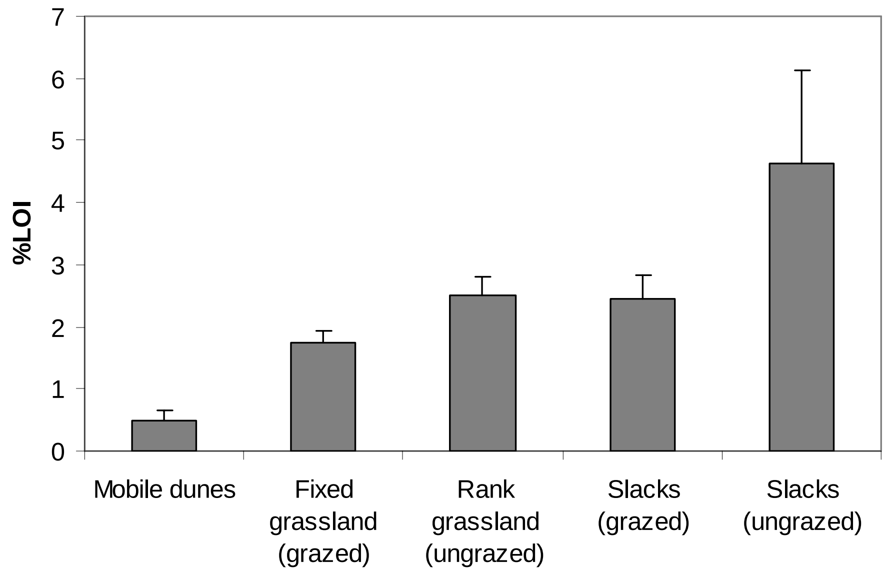


Figure 23. Soil organic matter content (to 15 cm) in dune habitats at Merthyr Mawr under > 20 years of natural grazing by rabbits, comparing grazed and ungrazed dry grassland and slacks. Mobile dunes are included for comparison. Bars show ±1 s.e.

4.7 Implications for soil development and N and C accumulation.

4.7.1 N and C accumulation in dunes

It is of great interest, with respect to the possible effects of both N deposition and climate change, to calculate the rates of carbon and nitrogen accumulation in this early stage of soil development. With the exception of mountain screes, dune soils are one of the few soil types in the UK where the very first stages of soil development can be studied, and their capacity to retain carbon may help understand processes governing carbon storage in other soil types.

The relationship between organic matter content and %C and %N content was tested using a wider database of the dry and wet dune habitats sampled in an earlier survey (Jones *et al.*, 2002), but restricting the analysis to sites from the west coast of the UK with a broadly similar climate to Newborough Warren. In the dry dunes, there is a reasonable correlation between %LOI and soil %N content (R^2 = 60.6 %), and between %LOI and soil %C content (R^2 = 63.6 %). Therefore, not surprisingly, the plots of N pools and C pools against soil age for Newborough (Figure 24) show a very similar relationship to that of %LOI. However, when the rate of N accumulation per year is calculated the figures are surprisingly high.

4.7.2 N accumulation in dry dune habitats

The rate of nitrogen accumulation was calculated for the soils which have clear bounded age estimates, excluding the mobile dunes. The average N accumulation rate in the dry dunes is 26.3 kg N ha^{-1} yr^{-1} (range 13.7 – 45.0 kg N ha^{-1} yr^{-1}). This figure is more than double the estimated annual N deposition figure of around 11 kg N ha^{-1} yr^{-1}. The nitrogen budget study at Merthyr Mawr (Jones *et al.*, 2005) which aimed to quantify leaching losses suggests that leaching removes 1.5 – 6.5 kg N ha^{-1} yr^{-1} in the dry dune grassland habitats, leaving calculated accumulation rates of 4.7 – 8.6 kg N ha^{-1} yr^{-1}. A leaching study in the Netherlands (ten Harkel *et al.*, 1998) indicated retention of around 30 % of additional N inputs (above background N deposition) in grazed calcareous dune grassland, under higher deposition loads. While there is some uncertainty in the estimates of soil age at Newborough, this uncertainty is not enough to account for this three- to five-fold difference in rates of accumulation. Therefore, these figures suggest there remains a large source of nitrogen unaccounted for.

One possible source of N is buried soil layers. The aerial photography from 1945-1951 shows large expanses of blown sand, yet within this there are areas which have obviously been fixed for some time. It is possible that some of these areas had been recently covered by blown sand at a depth which made their nutrients accessible to some of the deeper rooted plant species which subsequently colonised the sand. Dune species can be surprisingly deep rooted; Jones et al. (2005) found that even in the drier dune grasslands, species such as *Carex arenaria* and *Ononis repens* sent roots down to a depth of almost 1 m. *Ammophila arenaria* is well known to have extensive root systems (Fay & Jeffrey, 1995) and this is persistent, although not vigorous, in the semi-fixed (SD7) communities. Therefore, any buried soil layer within 1 m of the surface could potentially be accessible to colonising species. However, while buried soil layers would certainly help explain some of the higher rates of N accumulation observed, they do not occur everywhere and do not explain the generally high mean, or that the lowest rate of N accumulation is still greater than the calculated annual

deposition. The other most likely source of N in this system is biological N fixation. Legumes make up a large component of the flora in these semi-fixed communities, with a high cover of species such as *Ononis repens, Anthyllis vulneraria, Lotus corniculatus*, in the more open communities, and *Vicia* spp. in the taller vegetation. While N fixation rates have been estimated for blue-green algae – up to 25 kg N ha^{-1} yr^{-1} in damp sandy soils (Stewart, 1967) and for *Hippophae rhamnoides* (Stewart & Pearson, 1967), there have been no estimates for the common legumes in these early successional plant communities. The results presented here seem to suggest that, together with cyanobacteria, they may represent a significant extra source of nitrogen to the system in these very young soils.
These findings apply principally to the rapid phase of soil development and may not apply to the older soils. The fixed dune communities tend to contain fewer legumes and, in these habitats, extra N inputs in the form of atmospheric nitrogen deposition may represent a biologically significant extra source. Data from other semi-natural habitats suggest that atmospheric N deposition should increase soil development. Work by Evans et al. (in preparation) and de Vries et al. (2006), suggest that in other semi-natural systems (forests and heathlands), one extra unit of N incorporated in the system adds an extra 20 - 30 units of C. In the majority of these systems, leaching losses of N are negligible and most deposited N is retained until the system is unable to retain all the additional N, at which point the system is said to be N saturated and nitrate leaching starts to increase[1]. In the thin, largely calcareous dune soils of the UK on the other hand, N deposition is not fully retained, and the influence of N deposition depends on the proportion of N that is retained. This can only really be estimated using experimental studies in the field which manipulate the level of N inputs and then measure leaching losses. The data from the Dutch leaching experiment (ten Harkel *et al.*, 1998) are difficult to interpret since no dry deposition N data were presented (with the consequence that N fluxes in the unfertilised control were 160 % of bulk deposition inputs) and the experiment was small-scale and unreplicated. However, recalculation of the data for the calcareous dune grassland suggest that none of the additional N in the fertilisation treatment is retained in an ungrazed system, while 30 % of the additional N was retained in a rabbit-grazed system.

4.7.3 N accumulation in wet dune habitats

In the wet dune habitats, analysis of the wider field-survey data again shows a reasonable correlation between %LOI and soil %N content (R^2 = 57.5 %), and between %LOI and soil %C content (R^2 = 63.6 %). The plots of N pools and C pools against soil age at Newborough (Figure 25) also show a similar relationship to that of %LOI. The average rate of nitrogen accumulation calculated for the wet dune habitats is 30.2 kg N ha^{-1} yr^{-1} (range 11.9 – 57.5 kg N ha^{-1} yr^{-1}). This figure is even higher than for the dry dunes, although the range of figures is somewhat wider. The nitrogen budget study at Merthyr Mawr (Jones *et al.*, 2005) calculated that leaching losses from dune slacks were probably in the order of 3.4 – 4.4 kg N ha^{-1} yr^{-1}, giving a calculated accumulation rate of 6.7 kg N ha^{-1} yr^{-1}. Therefore, as with the dry dunes there must be large unaccounted sources of N to account for this five-fold difference. In addition to biological fixation, which may be primarily from blue-green algae at rates estimated at up to 25 kg N ha^{-1} yr^{-1} in the open sand habitats at Blakeney Point (Stewart, 1967), and buried soil layers, an additional source of N not likely to be present in most of the drier dune habitats is N from groundwater. The sand dune survey (Jones *et al.*, 2002) of

[1] Although some authors maintain that true N saturation only occurs when leaching losses equal inputs, i.e. 100% of inputs are leached. This point is seldom reached.

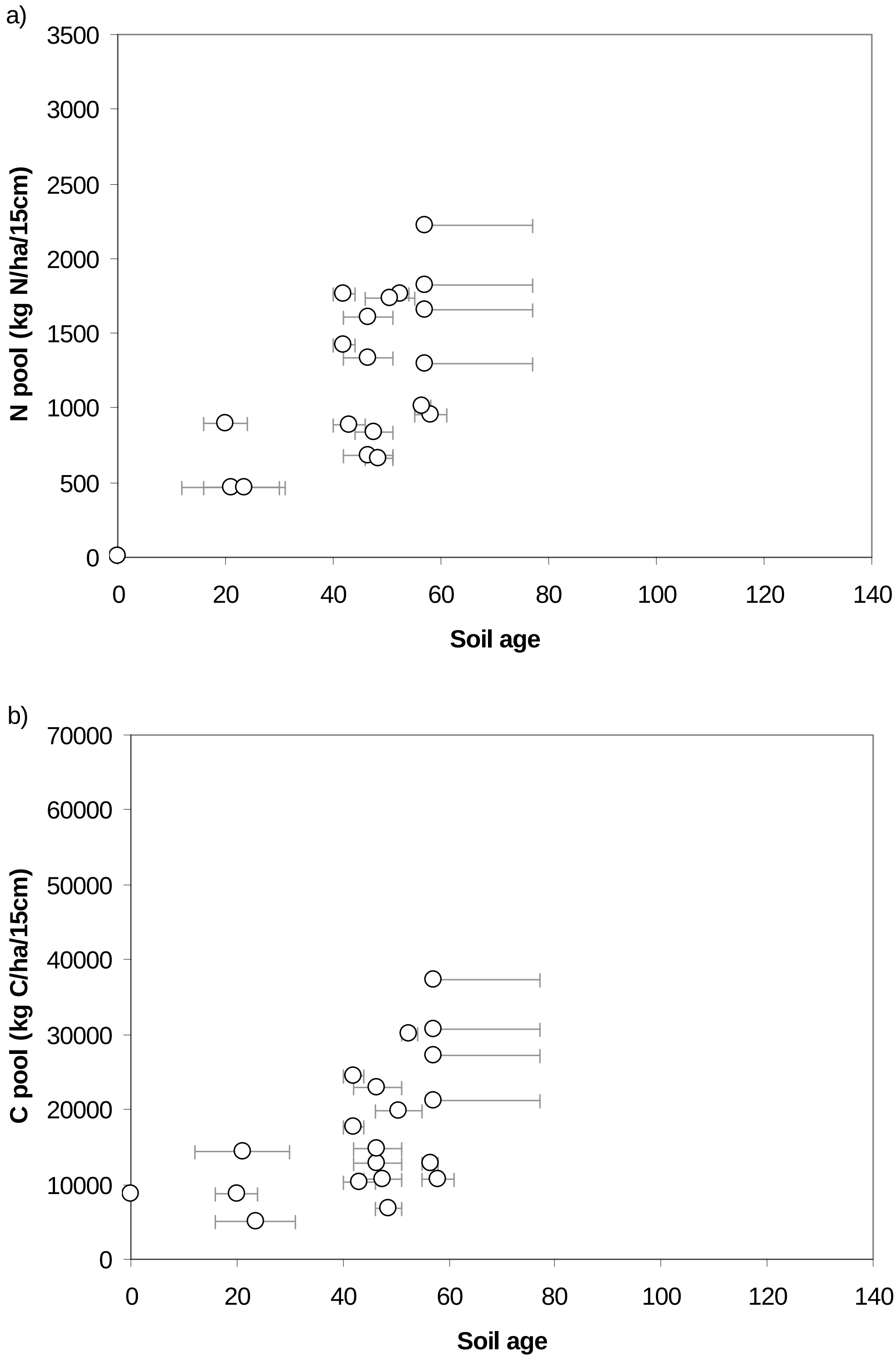
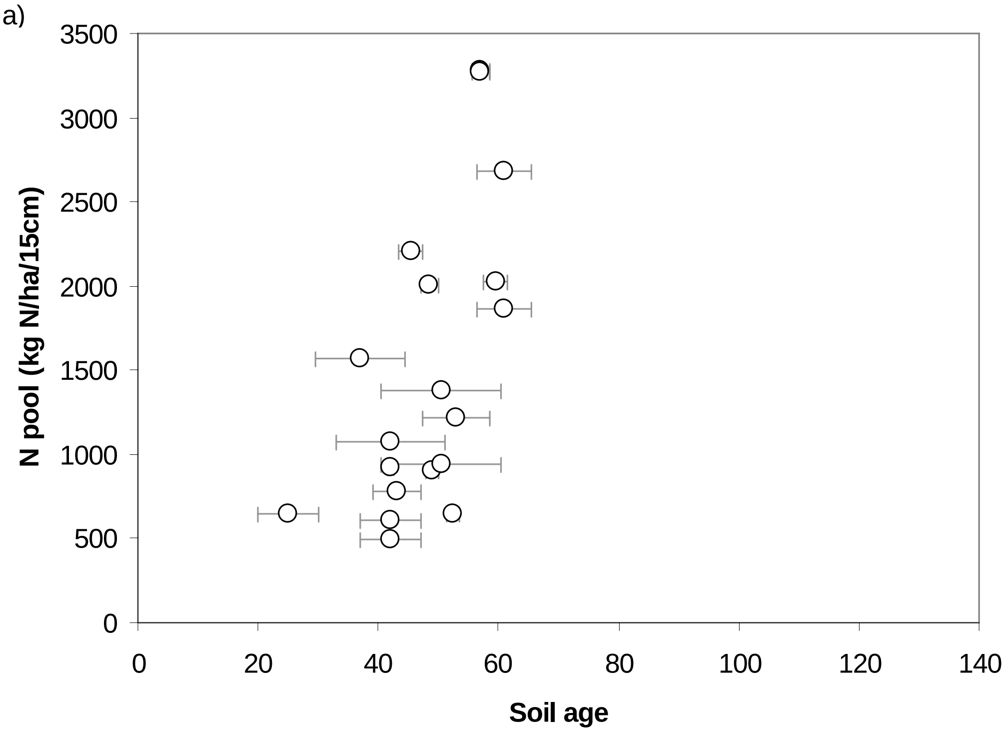


Figure 24. Soil pools of a) Nitrogen and b) Carbon, against age in the **dry dune habitats**.

a)



b)

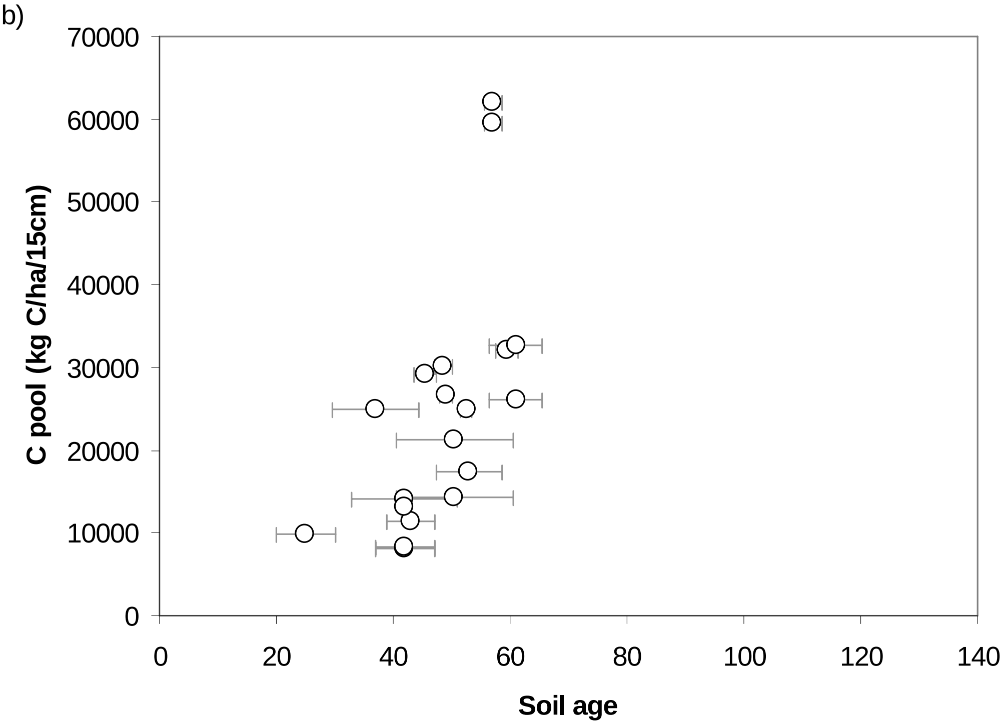


Figure 25. Soil pools of a) Nitrogen and b) Carbon, against age in the **wet dune habitats**.

English and Welsh sites found average concentrations of N of 1.19 mg N L^{-1} in the groundwater at Newborough, and subsequent work has confirmed similar levels (Mills, 2006). However, nitrogen fixation by blue-green algae may be sufficient to explain the observed accumulation rates. What is less well understood is whether increased deposition of inorganic N will affect rates of biological N fixation, with unknown consequences for community and soil development in dunes.

4.7.3 C:N ratio

The soil C:N ratio is often seen as an indicator of how N-saturated the system is. In coniferous forest soils, soil C:N ratio has been shown to control leaching rates, with an increase in leaching indicating N saturation below a threshold C:N ratio of around 35 (Dise *et al.*, 1998). However, different vegetation types produce or are associated with soils with different C:N ratios, and leaching occurs at different thresholds under different vegetation types (Figure 26) (Rowe *et al.*, 2006). The C:N ratio in sand dune soils is lower than in most other systems, including many other grasslands – with values between 12 and 20 (Figure 27) except for a few outliers. The C:N ratio is slightly higher in wet slacks than in dry dunes, however it remains more or less constant over the first 60 years of soil development. Since the C:N ratio remains constant, the relationship between %N and %LOI should also remain constant and this means we can use %LOI as a simple proxy for total N content in dune soils. However, the total N pool does not tell us how much nitrogen is available in the system. Available inorganic N is typically around 1 % of the total N pool, and has been shown to increase with succession (Olff *et al.*, 1993), also increasing with soil age in this study (Figure 28). However, it is not simply correlated with organic matter content and differs in dry and wet habitats for example. The consequences of N deposition are also unclear as the field survey conducted in 2001 showed a negative relationship of available N with N deposition (Jones *et al.*, 2004).

4.7.4 Effects of N deposition

While there were no significant correlations of N deposition at low levels with rates of organic matter accumulation in the first 60 years of soil development in this study, other research has shown effects on soil and the soil-plant system. Jones et al. (2004) showed correlations of soil C:N and available N with N deposition along an N deposition gradient spanning the critical load range. Experimental work in an N-manipulation study at Newborough Warren has shown increased retention of N in the above-ground biomass, particularly in mosses, at relatively low levels of added N within and just above the critical load range (Plassmann, 2006). Mosses act as a sponge and soak up much of the deposited N in oligotrophic ecosystems (Lamers et al., 2000). This stored N will subsequently be released to the soil system as the moss decomposes. It is possible to calculate the theoretical additional impact of N deposition on an established dry dune grassland over longer timescales using modelling approaches. Assuming an excess N deposition of around + 10 kg N ha^{-1} yr^{-1} on top of a background deposition of 10 kg N ha^{-1} yr^{-1}, and assuming 30 % retention based on the figures from ten Harkel et al. (1998), this would give an additional 3 kg N ha^{-1} yr^{-1} in a grazed system. Assuming a starting N pool of 2000 kg N ha^{-1}, equivalent to a well-established fixed dune grassland at Newborough, the additional N would amount to 300 kg N ha^{-1} over 100 years, i.e. 15 % of the starting soil N pool. However, these assumptions require testing, particularly in relation to the proportion of additional N that is retained in the soil-plant system under scenarios of increased N deposition.

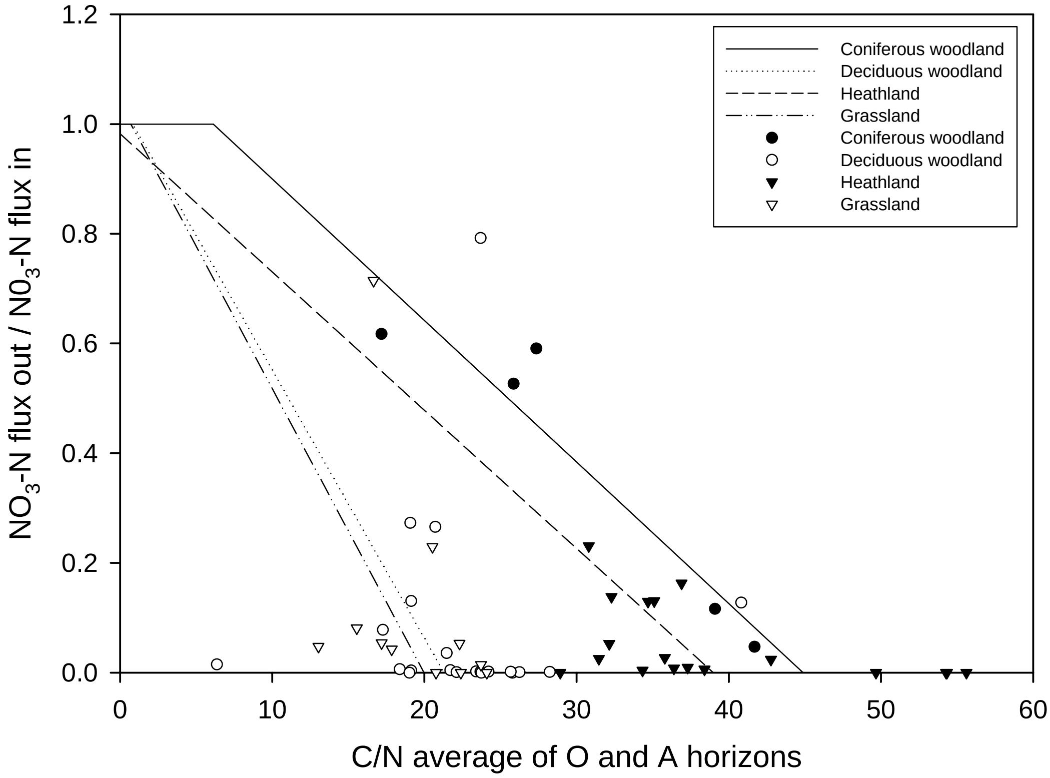


Figure 26. Soil C:N ratio as a control on NO3 leaching in a range of habitat types. Data from Rowe et al. (2006).

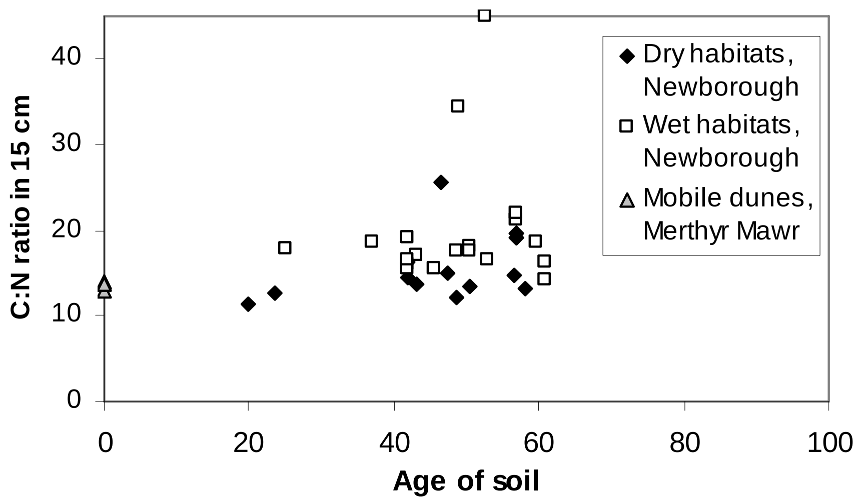


Figure 27. Changes in soil C:N (mol/mol) ratio in dry and wet dune habitats with soil age.

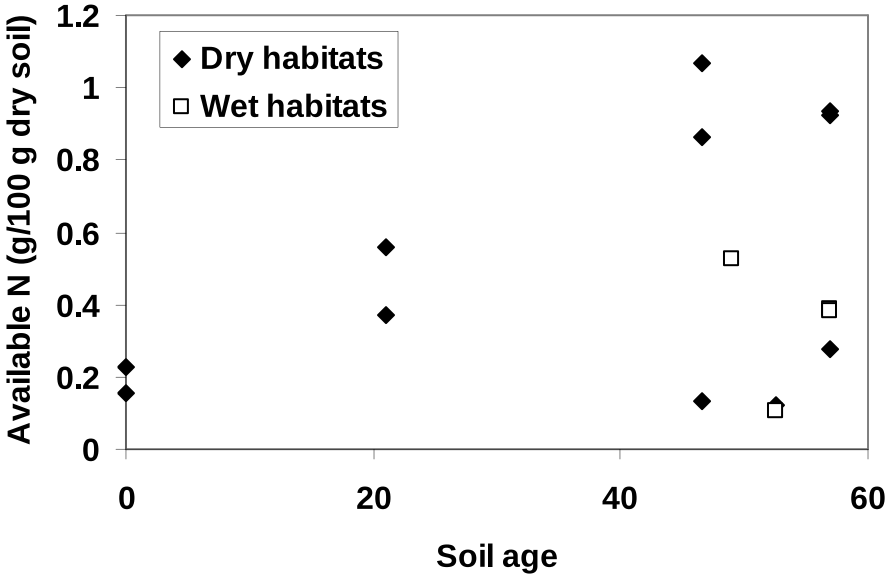


Figure 28. Changes in soil available N in the dry and wet dune habitats at Newborough Warren with soil age. Data from Jones et al. (2004).

4.7.5 Summary

In summary, we can use %LOI as a simple proxy for the amount of total N in the soil. Atmospheric N deposition could in theory increase the rate of soil development, however the effect of atmospheric N may differ in younger and older dune soils, depending on the magnitude of biological N fixation, the effects of N deposition on the N fixers, and the subsequent effects on soil development processes. Further work is required to assess retention rates of N in UK dune systems under a range of experimental N inputs.

4.8 Implications for vegetation community development.

In order to assess the implications of rates of soil accumulation for the associated vegetation community development, the subset of data for which NVC community information was available was utilised. This information was overlain on top of the soil development curves. Figure 29 shows the NVC community development in the dry habitats with time. As expected the mobile dunes (SD6e) and blowout communities (SD19) have a very low %LOI. The bulk of the rapid phase of soil development takes place while communities are classed as semi-fixed (SD7 communities). With a few exceptions, most of the fixed SD8 communities occur at the plateau of soil development, with the highest %LOI. This suggests that it takes a minimum of around 50 years for an SD8 community to develop at Newborough. The implications of soil development for plant diversity are also considered, with species richness plotted against soil age and against %LOI (Figure 30). These graphs show that species richness generally increases with soil development, and that the fixed SD8 communities are the most species rich. However, while they have the greatest diversity, this does not mean they contain the most desirable species from a dune conservation perspective. Further work is required to focus on the specific soil requirements for rare or important obligate dune plant species.

An anomaly in the increase in species richness with soil age is shown in Figure 30a for the blowout and disturbed communities (age range 10 – 30 years) which have a particularly high species richness relative to their %LOI. These communities are important for many of the rare plant species such as the grass *Mibora minima* and other winter annuals, therefore maintenance of these habitats is vitally important. Figure 30b illustrates the large variation in species richness once organic matter content exceeds a certain minimum threshold, and there are clearly other factors which control species richness. The interaction between soil development and management (grazing) may play a part, and further work would be useful to separate out reasons why some soils with a high organic matter content are particularly species poor, while others have double the level of plant diversity.
In the wet dune soils, there is no clear progression between NVC community types with increasing soil age or organic matter content (Figure 31). This suggests that factors other than simply age or soil development have a stronger control on the vegetation community. Two potential influences are hydrological regime, including groundwater chemistry which can be highly variable at a site (Jones et al., 2006), and grazing history. While both of these also affect soil development it seems apparent that they have a greater influence on vegetation community development than does soil organic matter content in these early stages of soil formation. The very poor relationships between species richness and soil age (Figure 32a) or organic matter content (Figure 32b) reinforce these conclusions. Unfortunately, the lack of older slack soil samples means that the implications for vegetation community can not be extrapolated beyond 60 years.

4.9 Extrapolating future rates of soil development and vegetation change.

This study has shown that accumulation of organic matter follows a sigmoidal curve in the early phases of soil development in two west coast dune systems. The rate of soil formation differs in dry and in wet dune habitats, although both follow the same relationship. Since organic matter accumulation rates are not linear over time, prediction of rates of soil development into the future depends entirely on your position on the curve. SigmaPlot v.10.0 was used to fit curves to the soil accumulation data for the dry and wet dune habitats for prediction purposes. Initial analysis showed that a Chapman, 4 parameter sigmoidal curve with an intercept (of the form f=y0+a*(1-exp(-b*x))^c) was the most appropriate curve to fit, based on the soil ages available for the Newborough samples and on the shape of soil-development curves at other sites from the literature. These curves are fitted for both %LOI and FH horizon thickness. Predictions of soil development from these curves and likely change over time are best done by visual fitting by eye, given the scatter in the data and uncertainties in soil ages beyond 60 years.

Part of the remit of this study was to provide predictions of likely rates of soil development over timescales of 20, 50 and 100 years hence. Figure 33 shows the fitted curves for the dry dune habitats, while Figure 34 shows the fitted curves for the wet dune habitats. Assuming soil development progresses unhindered, the early successional (SD 7c) or disturbed blow out communities (SD 19) of dry dune habitats will take around 40 years to become fully fixed SD 8 dune grasslands with a %LOI of around 3 %, and an FH horizon thickness of around 4 cm. In the wet dune habitats, soil development happens over a similar timescale but at a greater organic matter accumulation rate, reaching a typical %LOI of around 5 % and an FH horizon

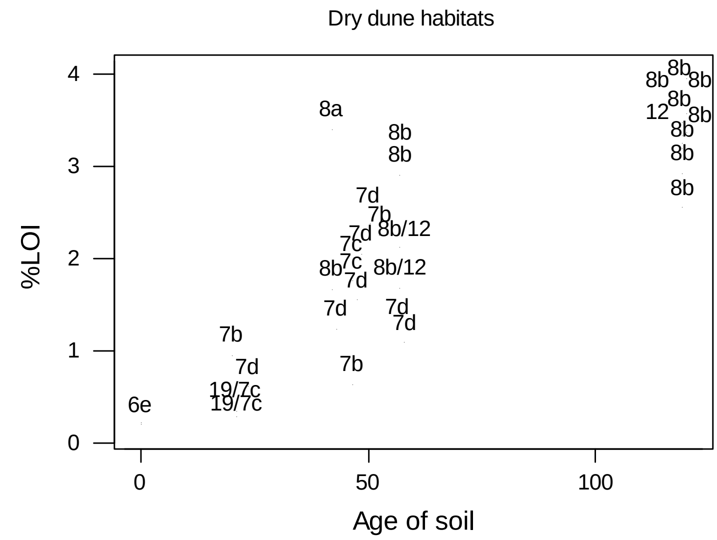


Figure 29. Vegetation community (NVC code) overlain on soil development curve for **dry dune habitats**.

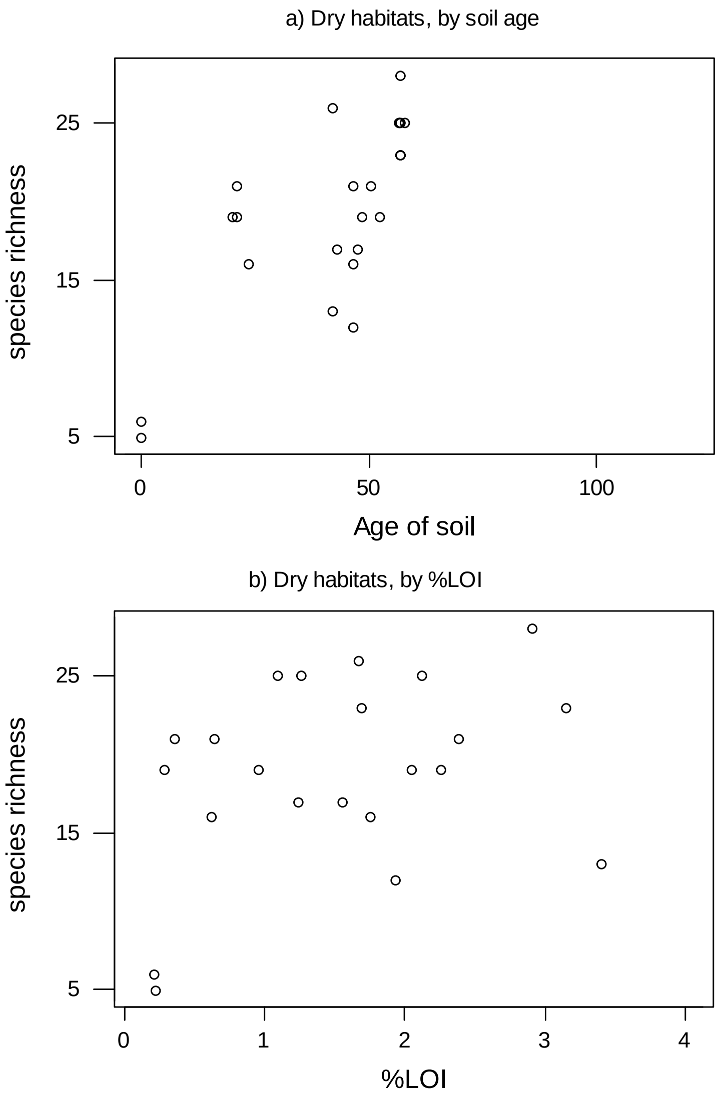


Figure 30. Species richness plotted against a) soil age, and b) %LOI, for **dry dune habitats**. Species richness only included for quadrats of 2 x 2 m.

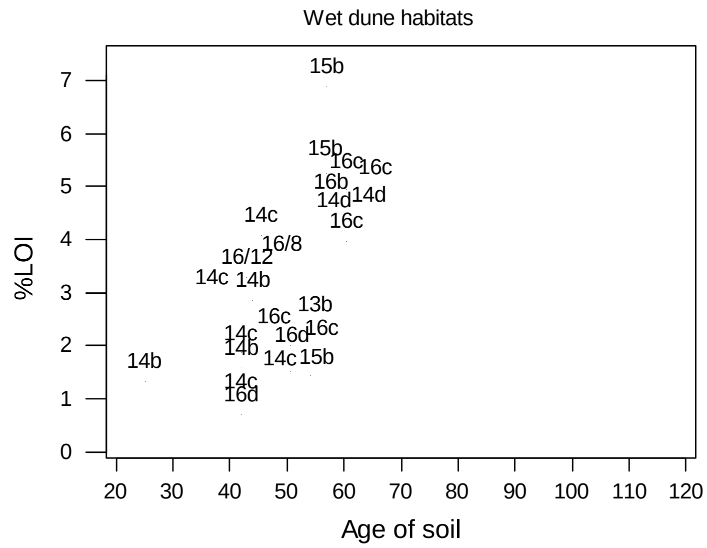


Figure 31. Vegetation community (NVC code) overlain on soil development curve for **wet dune habitats**.

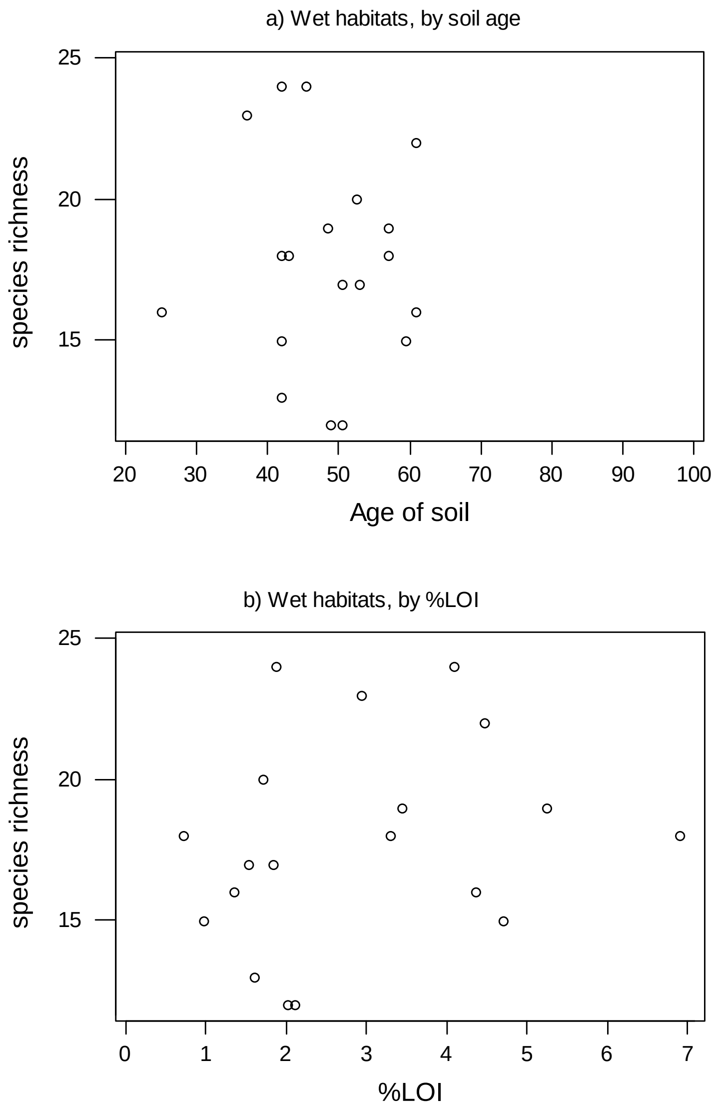


Figure 32. Species richness plotted against a) soil age, and b) %LOI, for **wet dune habitats**. Species richness only included for quadrats of 2 x 2 m.

thickness of around 6 cm by 60 years. Beyond around 60 years from the start of soil development in both habitat types the rate of soil accumulation slows considerably, and the data from other chronosequences such as reported for Southport (Figure 9) suggest that even over a timescale of around 100 years the rate of organic matter accumulation is so slow as to be barely measurable. Thus, predictions over any timescale depend very much on your starting point.

4.10 Establishing a soil monitoring methodology

There are two main purposes for soil monitoring, with different aims: Large scale monitoring of change across Wales, and site-based assessment of the condition of soil resources.

4.10.1 Large scale monitoring of change

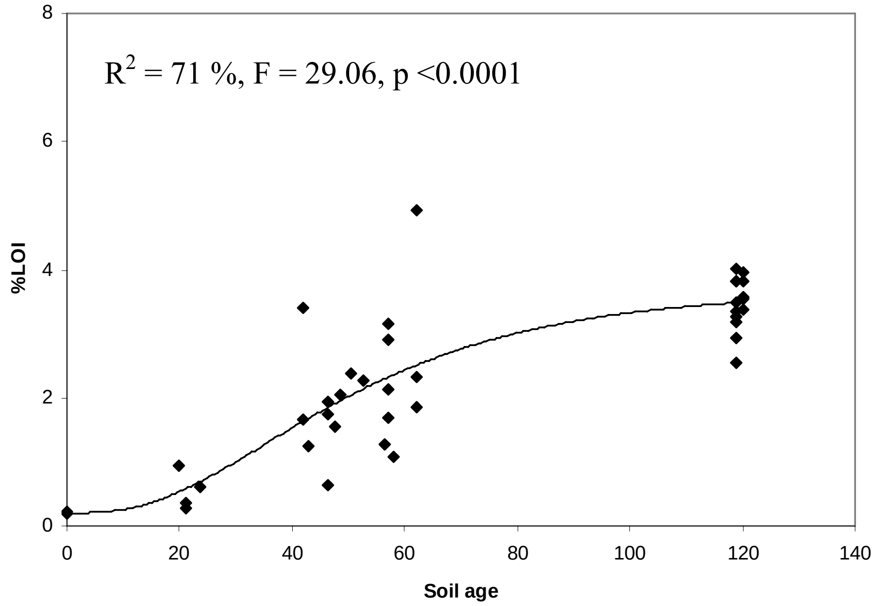
Monitoring of change over time is best done by a large-scale survey across a range of habitats and dune systems throughout Wales. A first survey would provide a baseline against which to measure change in future. This study has shown the benefits and the analytical opportunities afforded by a consistent soil sampling methodology and approach, and has also shown that inconsistent methodologies severely restrict the possible comparison between studies. The data analysed here represent the most consistent set of soil data from dune systems across Wales as far as is known. Therefore it is unlikely that other large datasets with archived soils exist which could be used to indicate change over time. This reinforces the need for a wider survey and the importance of establishing a consistent baseline at one time point which can be used to determine subsequent change over time. Standardising of the sampling and analysis protocols with those established for the current Countryside Survey would provide significant additional benefit in terms of interpretation and would allow comparison with wider datasets from other habitats. This survey should be repeated approximately every 10 years, which is a realistic timescale within which to pick up changes in soil development in the younger dune habitats.

A brief list of the key soil and vegetation characteristics which could be measured as part of such a survey is presented in Appendix C. However, the design of any large-scale survey should also take into account recommendations from the UK Soil Indicators Consortium and a forthcoming review report on setting up a National Soil Monitoring Network.

4.10.2 Site-based monitoring and assessment

There are a number of options for site-based assessments and monitoring of soil condition which use increasing complexity of techniques depending on the resources available. The basic principle is to compare soil characteristics from a particular site against either the typical soil development profiles established for Newborough (Figures 33 and 34 above), or against the typical values for a range of NVC communities presented in Figure 35 below. These are derived from all the Welsh and west coast English dune systems for which CEH holds data (Talacre Warren, Newborough, Harlech, Ynyslas, Pembrey, Kenfig, Merthyr Mawr, Whiteford Burrows, Ainsdale), and represent typical values for dune systems with broadly similar sand parent material and climatic conditions.

a) Fitted curve for %LOI, dry habitats



b) Fitted curve for FH thickness, dry habitats

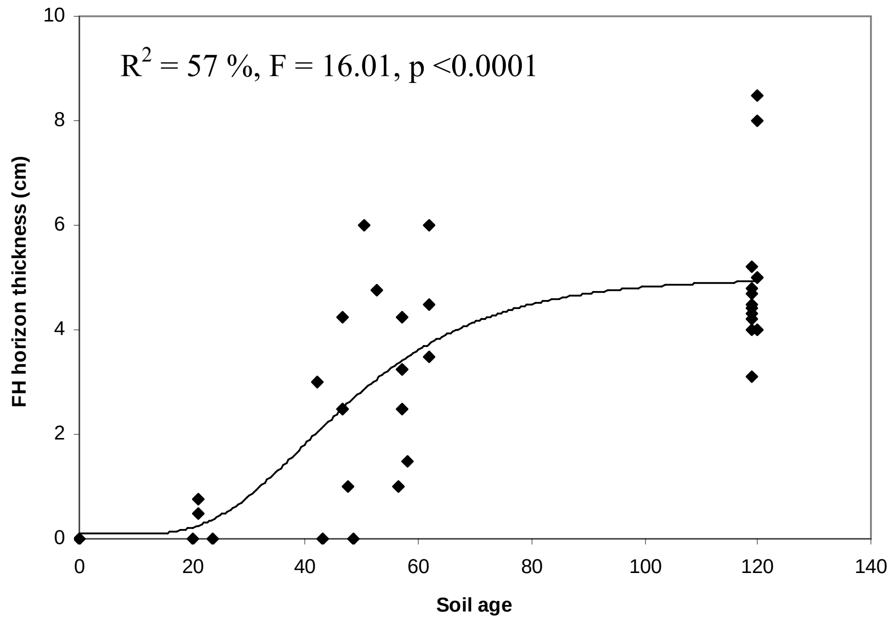
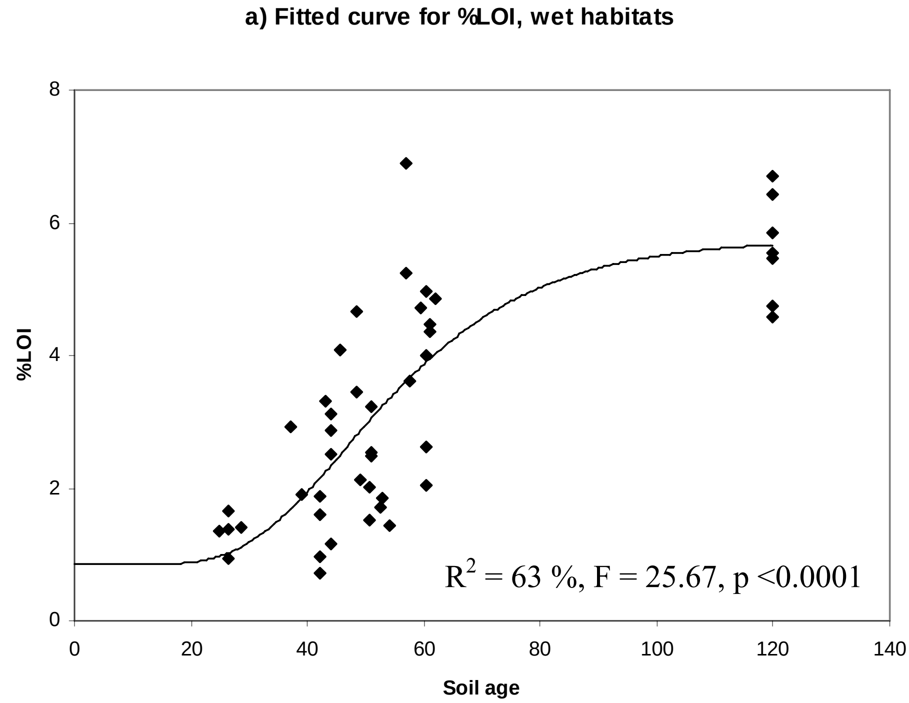


Figure 33. Fitted curves for rates of soil development in **dry dune habitats** with time, as either a) %LOI or b) FH horizon thickness (cm).



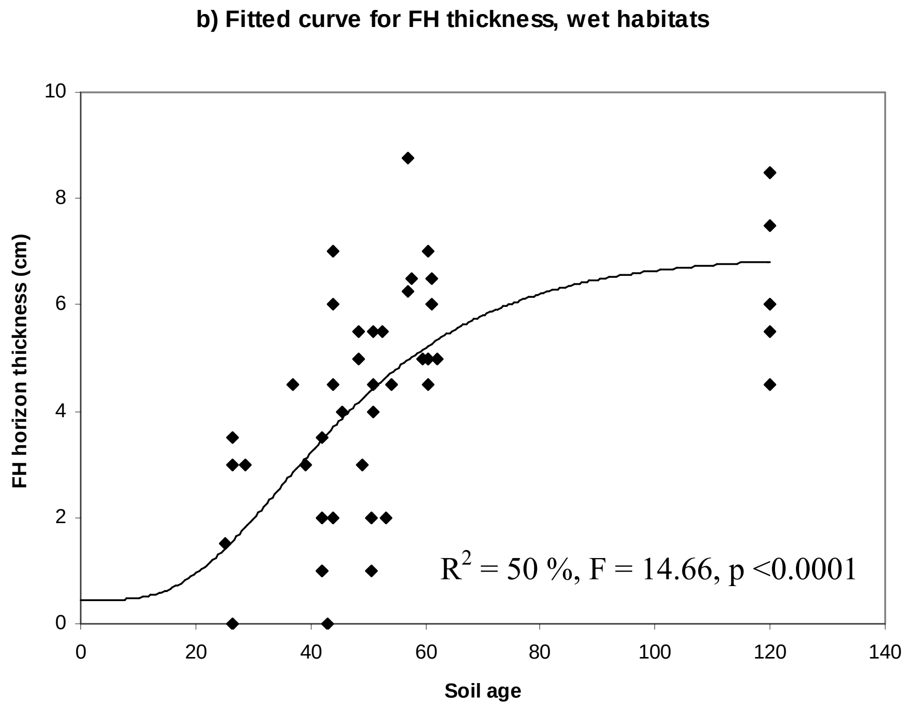


Figure 34. Fitted curves for rates of soil development in **wet dune habitats** with time, as either a) %LOI or b) FH horizon thickness (cm).

1. Although this study showed that soil organic matter content (measured as %LOI) was the most reliable measure of soil development, the simplest approach for assessing soil status is to measure FH (organic) horizon thickness. This can be done in the field with a trowel or small corer and requires little specialist knowledge or equipment. FH thickness is a more reliable measure of soil development in dune slacks than in dry dunes because there is usually less soil invertebrate activity and therefore a sharper soil profile. In some older dune soils, organic matter depth may well be greater than the standard 15 cm soil sampling; care should be taken to measure the full depth of the organic horizon.

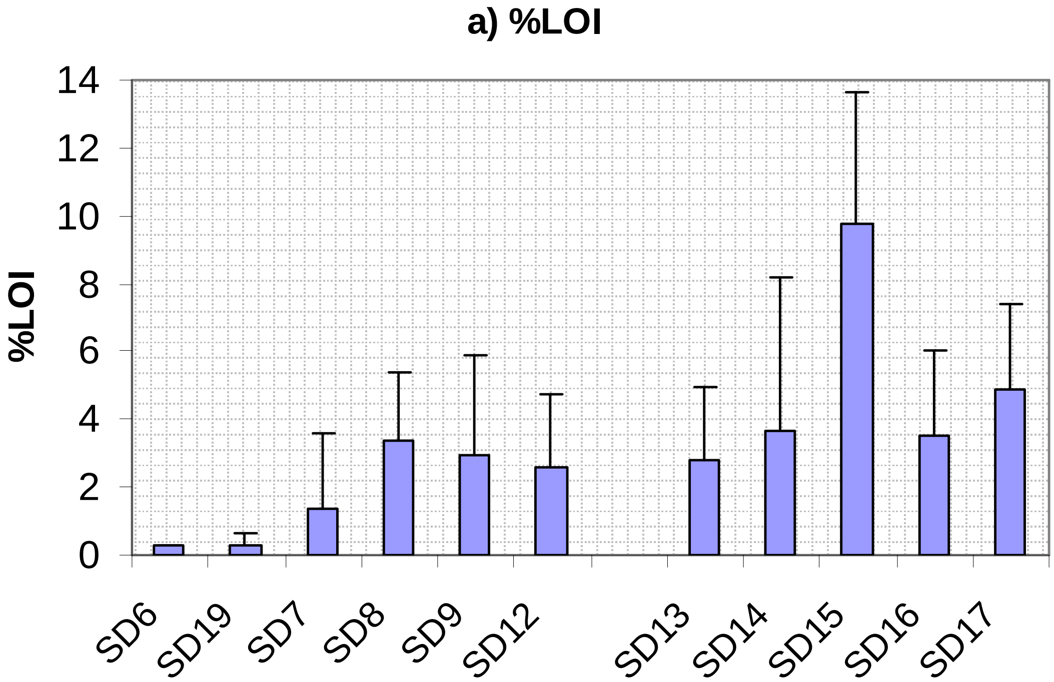
2. More accurate is to measure organic matter content of the soil directly (as %Loss On Ignition – LOI). This requires access to laboratory equipment including crucibles, scales accurate to 0.0001 g, a temperature controlled drying oven (to 105 °C) and muffle furnace (to 375 °C), and desiccators. The method is described in Appendix D. It is also important to measure the thickness of the FH and any other soil horizons within the 15 cm core and to obtain a measure of bulk density, in addition to measuring %LOI. Where the organic horizon extends below 15 cm, the full depth of the organic layer should be measured as in point 1 above, in addition to sampling to the standard depth of 15 cm for %LOI.

3. Since total N content is reasonably well correlated with organic matter content, it can be estimated from %LOI by the following equations for dry dunes (R^2 = 60.6 %) and dune slacks (R^2 = 57.5 %):

dry dunes: %N content = 0.0348 x %LOI + 0.0089
wet dunes: %N content = 0.0312 x %LOI + 0.0607

However, it would be more accurate to measure it in the laboratory using standard analytical procedures. Any systematic approach to assess site condition should follow laboratory procedures. Laboratory analysis of %C and %N content is considered preferable as this also allows monitoring of the soil C:N ratio which may change under continued high levels of N deposition. Soil C:N ratio in other semi-natural habitats has been shown to be a strong driver of species change. The standard methods of analysing %N content are by acid digest or by combustion in a CHN or CSN analyser. A number of companies offer %C and %N analysis on a commercial basis, and current costs are between £7 and £10 per sample including preparation. However, care needs to be taken that the detection limit of the combustion analyser is low enough to measure the low N contents in many dune soils, and that the carbonates in sand are acidified prior to combustion so that the carbonate does not affect the measurement of total C in the soil. If commercial analysis of soil samples is the preferred option, it is important to ensure these conditions can be met.

4. For more detailed information about the nutrient content and general fertility of a dune soil it is also important to measure the amount of available inorganic N (which tells you how much N is actually available for uptake by plants), the turnover of N (net N mineralisation), soil pH, soil $CaCO_3$ content, and available phosphorus content, with ideally some measure of depth to the water table and an indication of likely water table variation for dune slacks. Standard procedures for measuring most soil parameters are described in Allen (1989).



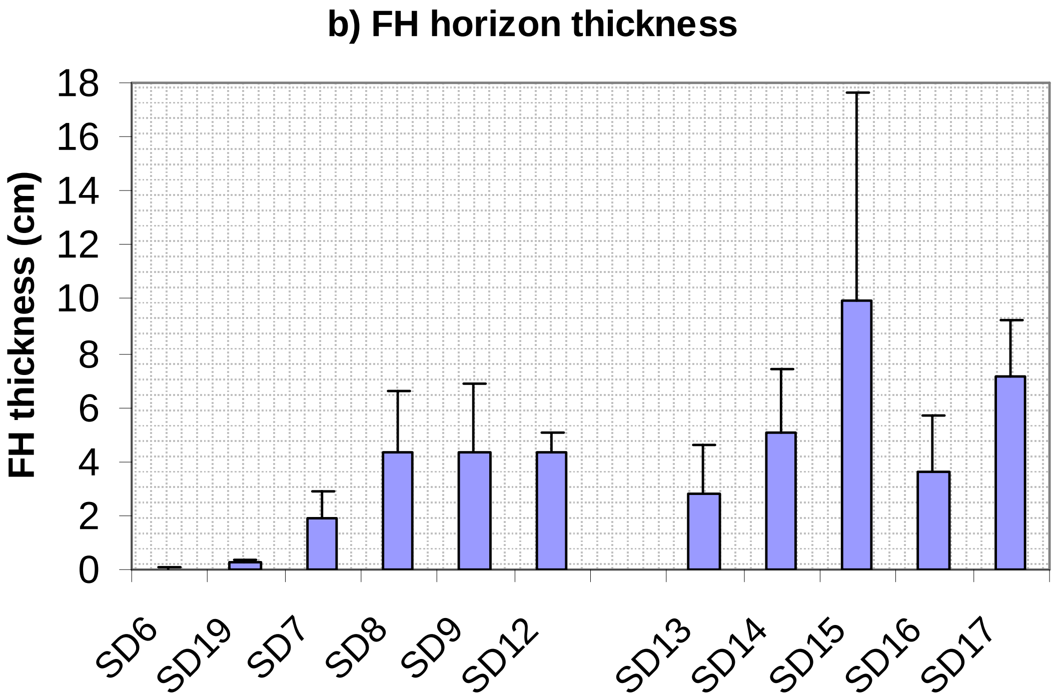


Figure 35. Mean soil characteristics for different NVC communities, based on data from Newborough, showing a) %LOI and b) FH horizon thickness. Bars show 1 standard deviation.

5. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER WORK

In summary, this study has provided important new information on the processes controlling the early stages of soil development in sand dunes, with implications for managing soil development and the associated vegetation communities. Climate appears to exert a large influence, both on the rate of initial colonisation by vegetation, but also on subsequent rates of soil development in both dry and wet dune habitats. Other abiotic factors such as slope, aspect and distance to the sea have varying degrees of influence on soil development, while local hydrological conditions and management by both natural and managed grazing also play a part. There is little direct evidence for effects of N deposition, but calculations based on work in other semi-natural habitats and evidence from an earlier field survey (Jones *et al.* 2004) suggest that N deposition is also likely to influence rates of soil development in dunes. The vegetation in dry dune habitats is fairly closely linked to the degree of soil development, while in the wet habitats, vegetation community is largely independent of soil development stage in the first 60 years.

With respect to the implications for site management, results suggest that retarding succession in the very early phases of vegetation establishment may prevent rapid soil development. Many of the open sand communities have a high biological importance for rare and threatened invertebrates such as the mining bee (*Colletes cunicularius*), and for the vegetation assemblages containing dune annuals. These must be regarded as a priority for conservation therefore the impetus for site management should be to maintain these communities in an open state and prevent succession to full cover. Once full vegetation cover establishes, then soil development tends to proceed rapidly. Managed or natural grazing can subsequently slow that rate of soil development but, unless there is significant disturbance by poaching, by rabbit activity, or by trampling pressure (including humans), then there is little that can stop soil development without recourse to large-scale mechanical methods of disturbance. However, it may be possible using less intensive methods to re-mobilise some of the younger successional communities which have attained full cover before soil development proceeds too far.

This study has also raised further questions and gaps in our knowledge. In order to address these, a number of recommendations are made for further work:

i) Further work is required to date the older soils in order to extend the soil development profile accurately beyond 60 years. Older soils identified in this study could be dated accurately, particularly the fixed dune grassland around the edges of the Warren, but also including the older soil plains within the Warren such as those near the sea and on the spit, all of which pre-date 1945. There is also an urgent need to extend the chronosequence for the dune slacks as there are no accurate dates beyond 60 years in this habitat.

ii) This work could extend to sampling other locations for which accurate ages have been established in other studies, such as at Aberffraw and perhaps further afield on the Sefton coast. Vegetation assemblages and characteristics should be assessed in tandem with soil characterisation for these older soils. Palaeosols should also be considered as a potential resource and a preliminary assessment of their %C and %N content is recommended.

iii) The work assessing how species richness changes with degree of soil development undertaken here should be extended to the Common Standards Monitoring (CSM) 'positive' and 'negative' indicator species, to understand in greater detail whether increasing %LOI is actually detrimental to the dune vegetation assemblages and to what extent they form an important part of the mosaic of different dune habitats.

iv) Greater understanding is required of the requirements for those rare species most suited to semi-fixed/open habitats (e.g. mining bees) and see how their abundance changes with the degree of vegetation cover and soil development.

v) A lysimeter study studying the leachate chemistry should be incorporated within the N addition *x* grazing experiment in order to accurately measure the proportion of extra N that is retained in a UK dune system. The only other source of information on this subject derives from a Dutch study which was small scale, unreplicated, and was conducted under higher background N deposition conditions. This will be the only way to categorically state that N deposition is a bad thing in the long term.

vi) The high rates of N accumulation suggest significant additional sources of N other than atmospheric N. Work is urgently needed to quantify the inputs from biological N fixation in dry and wet dune habitats. A secondary component of this work would be to assess whether atmospheric deposition of predominantly inorganic N switches off or reduces the magnitude of biological N fixation.

vii) The long-term effects of forestry on dune soil development at Newborough could be assessed by repeating key aspects of the forest survey conducted by Hill & Wallace. Such a study would be invaluable in measuring change and would be unique in having 2 time-points. It could also be modified to calculate the carbon storage in both the standing crop and the soil at Newborough.

6. REFERENCES

Allen, S.E., 1989. Chemical analysis of ecological materials. Blackwell Scientific Publications, Oxford.

Berendse, F., Lammerts, E.J., Olff, H., 1998. Soil organic matter accumulation and its implications for nitrogen mineralization and plant species composition during succession in coastal dune slacks. Plant Ecology 137 (1), 71-78.

Carter, R.W.G., 1988. Coastal Environments. Academic Press, London.

de Vries, W., Reinds, G.J., Gundersen, P., Sterba, H., 2006. The impact of nitrogen deposition on carbon sequestration in European forests and forest soils. Global Change Biology 12, 1151-1173.

Dise, N.B., Matzner, E., Forsius, M., 1998. Evaluation of organic horizon C:N ratio as an indicator of nitrate leaching in conifer forests across Europe. Environmental Pollution 102, 453-456.

Erlandson, J.M., Rick, T.C., Peterson, C., 2005. A geoarchaeological chronology of Holocene dune building on San Miguel Island, California. Holocene 15 (8), 1227-1235.

Ernst, W.H.O., Slings, Q.L., Nelissen, H.J.M., 1996. Pedogenesis in coastal wet dune slacks after sod-cutting in relation to revegetation. Plant and Soil 180 (2), 219-230.

Evans, C.D., Pilkington, M.G., Caporn, S., in preparation. Modelling nitrogen saturation and carbon accumulation in moorland soils in response to nitrogen deposition.

Fay, P.J., Jeffrey, D.W., 1995. The nitrogen cycle in sand-dunes. In: Jeffrey, D.W., Jones, M.B., McAdam, J.H. (Eds.), Irish grasslands - their biology and management. Royal Irish Academy, Dublin.

Fowler, D., O'Donoghue, M., Muller, J.B.A., Smith, R.I., Dragosits, U., Skiba, U., Sutton, M.A., Brimblecombe, P., 2004. A chronology of nitrogen deposition in the UK between 1900 and 2000. Water Air and Soil Pollution Focus 4, 9-23.

Gerlach, A., Albers, E.A., Broedlin, W., 1994. Development of the nitrogen cycle in the soils of a coastal dune succession. Acta Botanica Neerlandica 43 (2), 189-203.

Hesse, P.P., Simpson, R.L., 2006. Variable vegetation cover and episodic sand movement on longitudinal desert sand dunes. Geomorphology 81 (3-4), 276-291.

Hewett, D.G., 1982. Grazing studies on sand dunes., Institute of Terrestrial Ecology. Annual Report 1981.

Hewett, D.G., 1985. Grazing and mowing as management tools on dunes. Vegetatio 62 (1-3), 441-447.

Hill, M.O., Wallace, H.A., 1987. Survey of Newborough Forest. Final report to Forestry Commission. FC/NERC Contract F3CR31/D4/01, Institute of Terrestrial Ecology (Natural Environment Research Council).

Hill, M.O., Wallace, H.A., 1989. Vegetation and environment in afforested sand dunes at Newborough, Anglesey. Forestry 62 (3), 249-267.

Hugenholtz, C.H., Wolfe, S.A., 2005. Recent stabilization of active sand dunes on the Canadian prairies and relation to recent climate variations. Geomorphology 68 (1-2), 131-147.

Jones, M.L.M., Hayes, F., Brittain, S.A., Haria, S., Williams, P.D., Ashenden, T.W., Norris, D.A., Reynolds, B., 2002. Changing nutrient budgets of sand dunes: Consequences for the nature conservation interest and dune management. 2. Field survey. Contract Report September 2002. CCW Contract No: FC 73-01-347. CEH Project No: C01919., Centre for Ecology and Hydrology, Bangor.

Jones, M.L.M., Wallace, H.L., Norris, D., Brittain, S.A., Haria, S., Jones, R.E., Rhind, P.M., Reynolds, B.R., Emmett, B.A., 2004. Changes in vegetation and soil characteristics in

coastal sand dunes along a gradient of atmospheric nitrogen deposition. Plant Biology 6 (5), 598-605.
Jones, M.L.M., Pilkington, M.G., Healey, M., Norris, D.A., Brittain, S.A., Tang, Y.S., Reynolds, B., 2005. Determining a nitrogen budget for Merthyr Mawr sand dune system. Final report for Countryside Council for Wales. CEH Project No: C02352NEW, CCW Contract No: FC 72-02-59. May 2005.
Jones, M.L.M., Reynolds, B., Brittain, S.A., Norris, D.A., Rhind, P.M., Jones, R.E., 2006. Complex hydrological controls on wet dune slacks: The importance of local variability. Science of the Total Environment 372 (1), 266-277.
Ketner-Oostra, R., van der Peijl, M.J., Sykora, K.V., 2006. Restoration of lichen diversity in grass-dominated vegetation of coastal dunes after wildfire. Journal of Vegetation Science 17 (2), 147-156.
Knight, M., Thomas, D.S.G., Wiggs, G.F.S., 2004. Challenges of calculating dunefield mobility over the 21st century. Geomorphology 59 (1-4), 197-213.
Kooijman, A.M., Dopheide, J.C.R., Sevink, J., Takken, I., Verstraten, J.M., 1998. Nutrient limitations and their implications on the effects of atmospheric deposition in coastal dunes; lime-poor and lime- rich sites in the Netherlands. Journal of Ecology 86 (3), 511-526.
Kooijman, A.M., Besse, M., 2002. The higher availability of N and P in lime-poor than in lime- rich coastal dunes in the Netherlands. Journal of Ecology 90 (2), 394-403.
Kooijman, A.M., 2004. Environmental problems and restoration measures in coastal dunes in the Netherlands. In: Martinez, M.L., Psuty, N.P. (Eds.), Coastal dunes, ecology and conservation. Ecological Studies 171. Springer, Berlin, pp. 243-258.
Lamers, L.P.M., Bobbink, R., Roelofs, J.G.M., 2000. Natural nitrogen filter fails in polluted raised bogs. Global Change Biology 6, 583-586.
Lammerts, E.J., Pegtel, D.M., Grootjans, A.P., van der Veen, A., 1999. Nutrient limitation and vegetation changes in a coastal dune slack. Journal of Vegetation Science 10 (1), 111-122.
Lancaster, N., Helm, P., 2000. A test of a climatic index of dune mobility using measurements from the southwestern United States. Earth Surface Processes and Landforms 25 (2), 197-207.
Levin, N., Kidron, G.J., Ben-Dor, E., 2006. The spatial and temporal variability of sand erosion across a stabilizing coastal dune field. Sedimentology 53 (4), 697-715.
McClaugherty, C., Berg, B., 1987. Cellulose, lignin, and nitrogen concentrations as rate regulating factors in late stages of forest litter decomposition. Pedobiologia 30, 101-112.
Mills, R.T.E., 2006. Investigating the impact of pine plantation forestry on the groundwater biogeochemistry of a coastal dune system at Newborough, Anglesey. MSc Thesis, University of Wales Bangor.
Mohd-Said, M.N., 1999. Effects of anthropogenic nitrogen inputs on dune grassland. PhD Thesis, University of Wales, Bangor.
Nadelhoffer, K.J., Downs, M.R., Fry, B., 1999. Sinks for ^{15}N enriched additions to an oak forest and a red pine plantation. Ecological Applications 9, 72-86.
Olff, H., Huisman, J., Vantooren, B.F., 1993. Species dynamics and nutrient accumulation during early primary succession in coastal sand dunes. Journal of Ecology 81 (4), 693-706.
Pastor, J., Dewey, B., Naiman, R.J., McInnes, P.F., Cohen, Y., 1993. Moose browsing and soil fertility in the boreal forest of Isle Royale National Park. Ecology 74, 52-61.
Perkins, D.F., 1978. The distribution and transfer of energy and nutrients in the *Agrostis-Festuca* grassland ecosystem. In: Heal, O.W., Perkins, D.F. (Eds.), Production

ecology of British moors and montane grasslands. Ecological Studies 27. Springer-Verlag, Berlin, pp. 374-395.
Plassmann, K., 2006. Effects of grazing and nitrogen deposition on sand dune systems. PhD Thesis, University of Wales, Bangor.
Ranwell, D., 1959. Newborough Warren, Anglesey. 1. The dune system and dune slack habitat. Journal of Ecology 47, 571-600.
Ranwell, D., 1960. Newborough Warren, Anglesey. 3. Changes in the vegetation on parts of the dune system after the loss of rabbits by myxomatosis. Journal of Ecology 48, 385-395.
Rawes, M., Heal, O.W., 1978. The blanket bog as part of a Pennine moorland. In: Heal, O.W., Perkins, D.F. (Eds.), Production ecology of British moors and montane grasslands. Ecological Studies 27. Springer-Verlag, Berlin, pp. 224-243.
Ritchie, M.E., Tilman, D., Knops, J.M.H., 1998. Herbivore effects on plant and nitrogen dynamics in Oak savanna. Ecology 79, 165-177.
Rowe, E.C., Evans, C.D., Emmett, B.A., Reynolds, B., Helliwell, R.C., Coull, M.C., Curtis, C.J., 2006. Vegetation type affects the relationship between soil carbon to nitrogen ratio and nitrogen leaching. Water Air and Soil Pollution 177 (1-4), 335-347.
Ruess, R.W., McNaughton, S.J., 1987. Grazing and the dynamics of nutrient and energy regulated microbial processes in the Serengeti grasslands. Oikos 49, 101-110.
Salisbury, E.J., 1922. The soils of Blakeney Point: A study of soil reaction and succession in relation to the plant covering. Annals of Botany 36, 391-431.
Salisbury, E.J., 1925. Note on the Edaphic Succession in Some Dune Soils with Special Reference to the Time Factor. Journal of Ecology 13 (2), 322-328.
Sevink, J., 1991. Soil development in the coastal dunes and its relation to climate. Landscape Ecology 6, 49-56.
Stewart, W.D.P., 1967. Transfer of biologically fixed nitrogen in a sand dune slack system. Nature 214, 603-604.
Stewart, W.D.P., Pearson, M.C., 1967. Nodulation and nitrogen-fixation by H*ippophae rhamnoides* L. in the field. Plant and Soil 26, 348-360.
Syers, J.K., Adams, J.A., Walker, T.W., 1970. Accumulation of organic matter in a chronosequence of soils developed on wind-blown sands in New Zealand. Journal of Soil Science 21, 146-153.
Talbot, M.R., 1984. Late Pleistocene rainfall and dune building in the Sahel. Palaeoecology of Africa 16, 203-214.
ten Harkel, M.J., van der Meulen, F., 1996. Impact of grazing and atmospheric nitrogen deposition on the vegetation of dry coastal dune grasslands. Journal of Vegetation Science 7 (3), 445-452.
ten Harkel, M.J., van Boxel, J.H., Verstraten, J.M., 1998. Water and solute fluxes in dry coastal dune grasslands: the effects of grazing and increased nitrogen deposition. Plant and Soil 202 (1), 1-13.
Tsoar, H., 2005. Sand dunes mobility and stability in relation to climate. Physica a-Statistical Mechanics and Its Applications 357 (1), 50-56.
van den Berg, L.J.L., Tomassen, H.B.M., Roelofs, J.G.M., Bobbink, R., 2005. Effects of nitrogen enrichment on coastal dune grassland: A mesocosm study. Environmental Pollution 138 (1), 77-85.
White, D.J.B., 1961. Some observations on the vegetation of Blakeney Point, Norfolk, following the disappearance of rabbits in 1954. Journal of Ecology 49, 113-118.
Wilson, K., 1960. The time factor in the development of dune soils at South Haven Peninsula, Dorset. Journal of Ecology 48, 341-359.

APPENDIX A

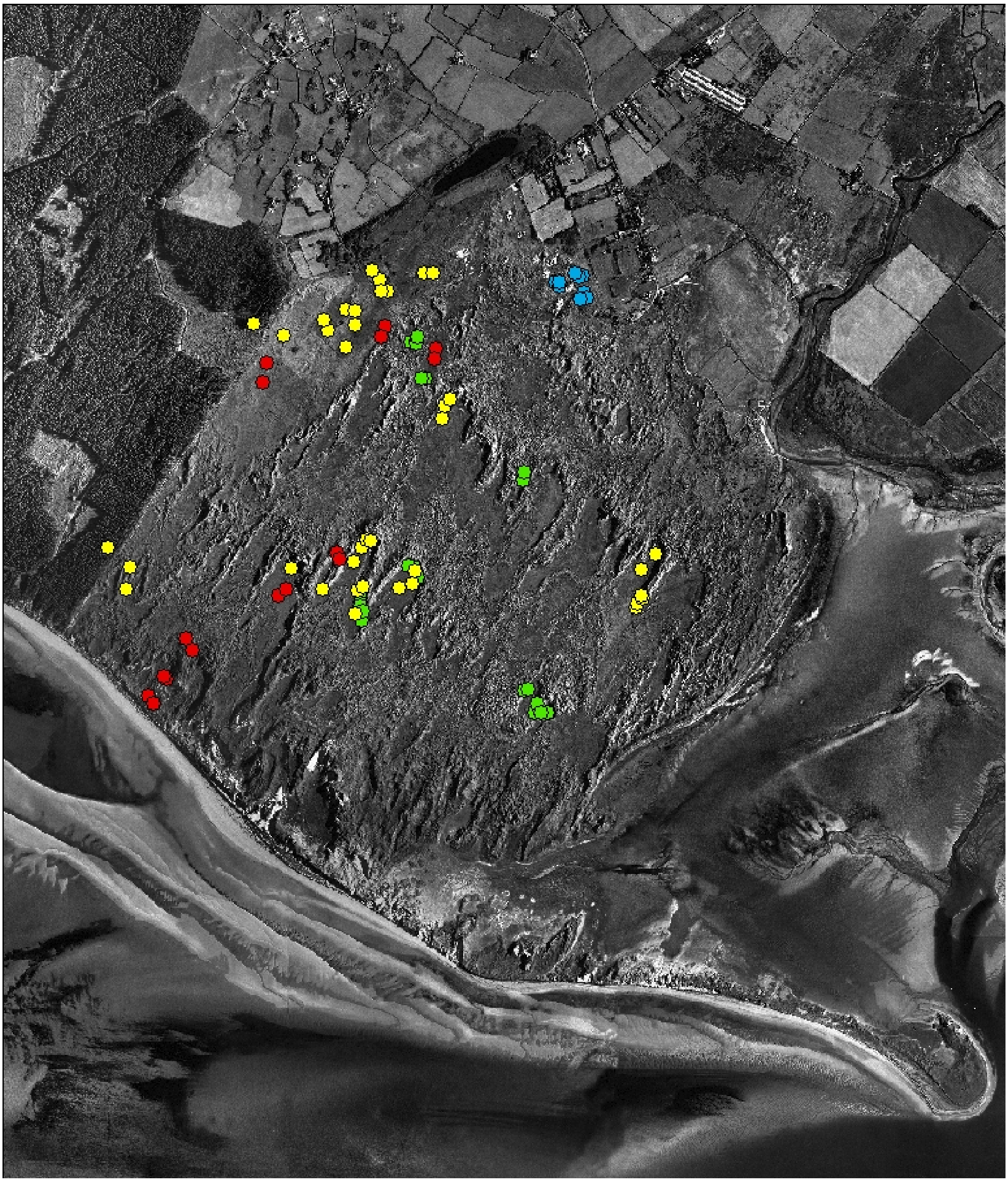


Figure 34. Sampling locations at Newborough Warren analysed as part of this study. Red dots – sand dune survey (Jones et al. 2002, 2004), Green dots – Defra rare species study (ongoing), Blue dots – Nitrogen x grazing manipulation study (ongoing), Yellow dots – Additional sampling as part of this study.

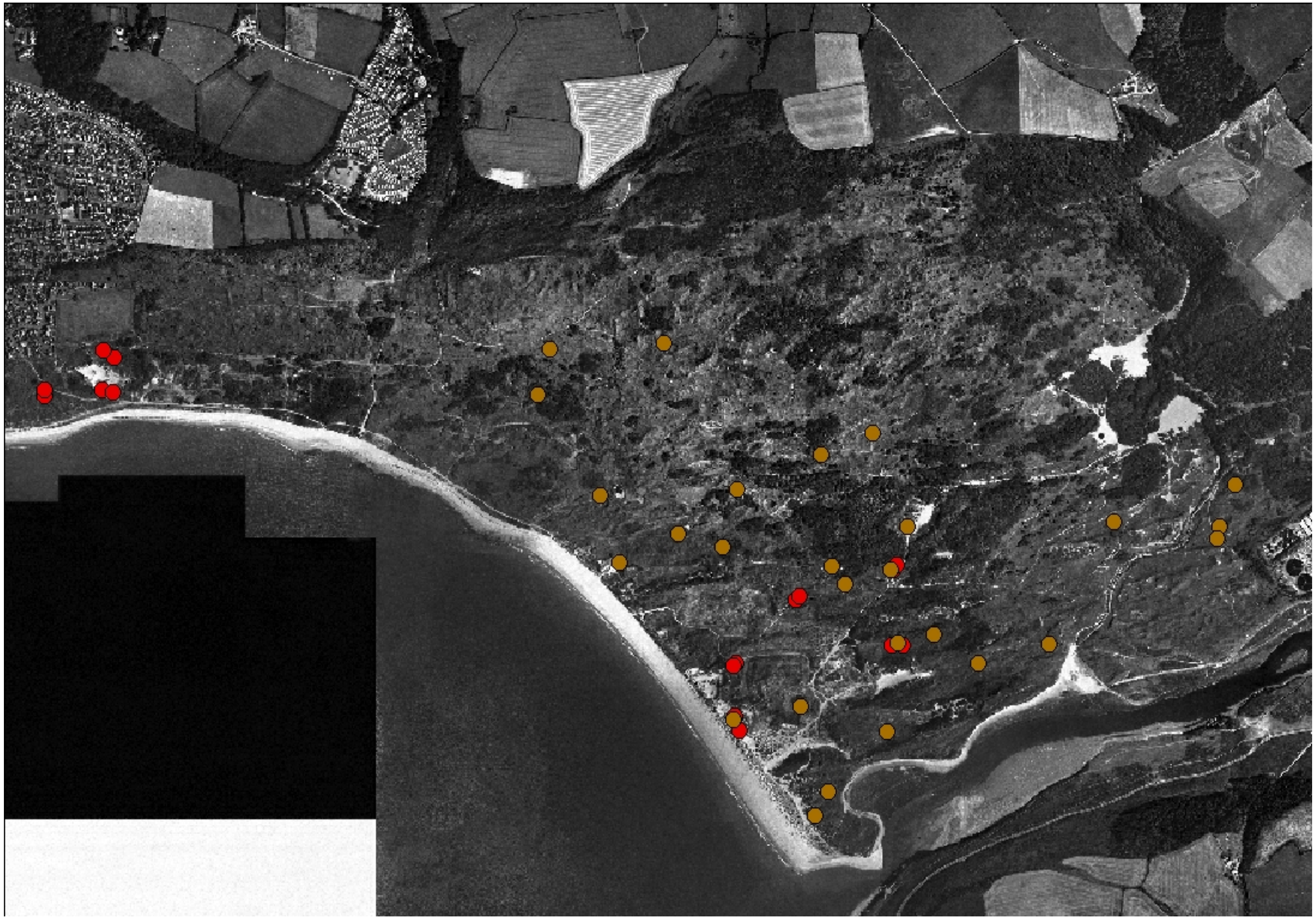


Figure 35. Sampling locations at Merthyr Mawr analysed as part of this study. Red dots – sand dune survey (Jones et al. 2002, 2004), Brown dots – Nitrogen budget study in key dune habitats (Jones et al, 2005).

APPENDIX B

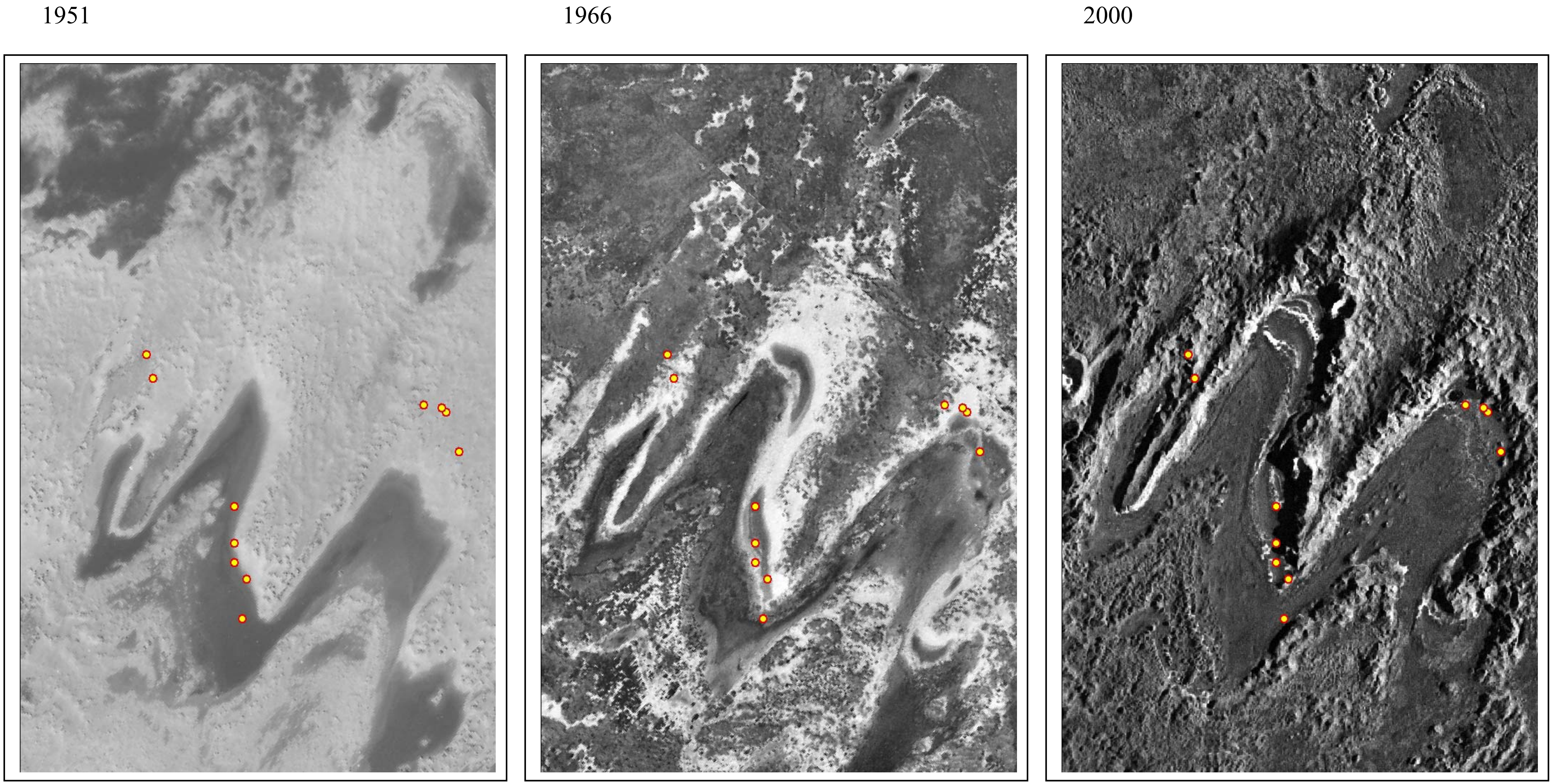


Figure 36. Aerial photography sequence for a dune slack at Newborough showing progressive development of the morphological feature, leaving readily identifiable traces of earlier features which can be aged and sampled. This example shows sampling locations from the Defra rare species study.

1951 1966 2000

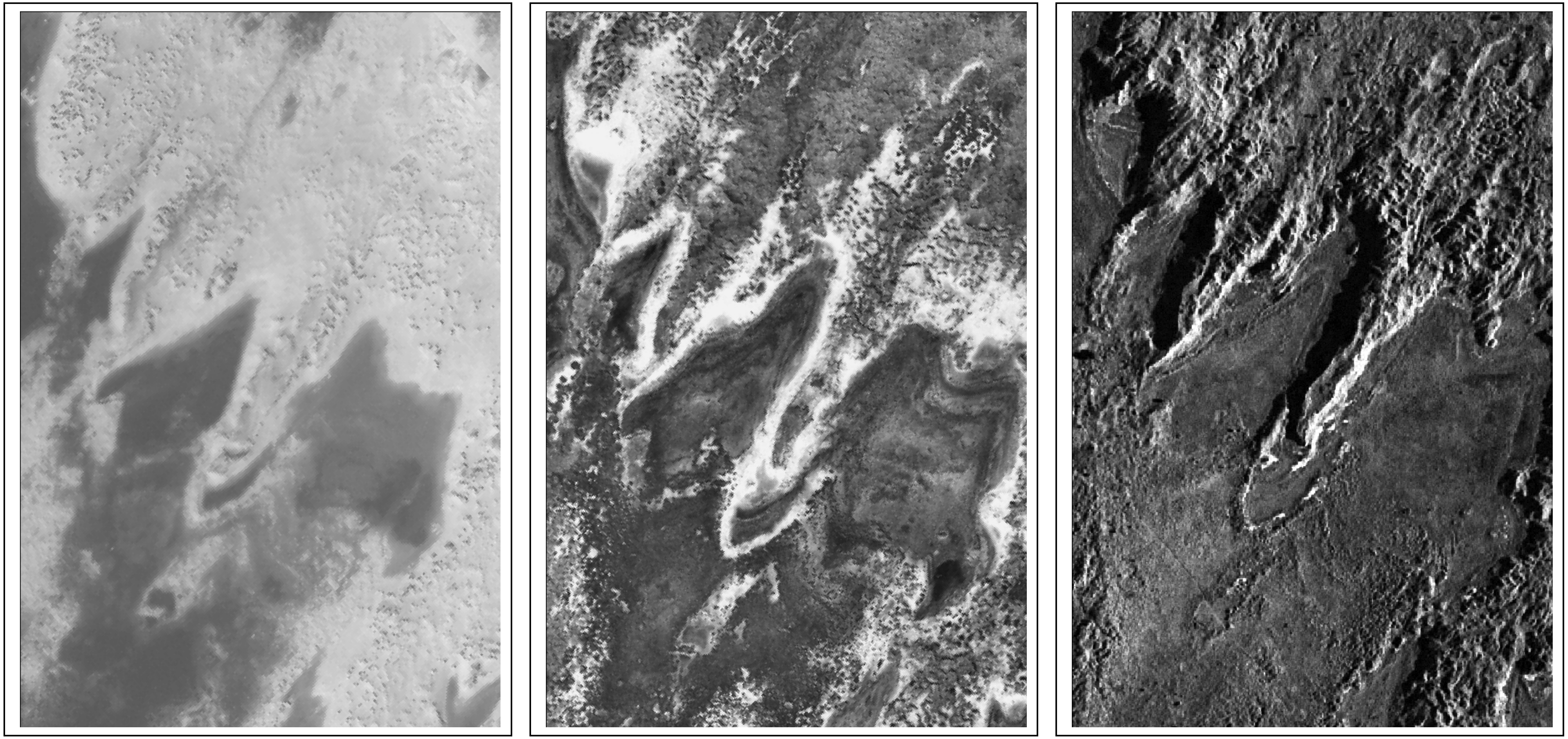


Figure 37. Second example of dune slack chronosequences at Newborough Warren.

APPENDIX C

Basic recommended set of measurements which might form part of a wider sand dune soil monitoring programme in Wales.

<u>Recommended soil characteristics to sample (core to depth of 15 cm):</u>
Characterise and measure thickness of soil horizons
%LOI
Bulk density
Soil pH (measured in both water and $CaCl_2$), to possibly include a separate analysis of soil pH of the litter layer.
Soil $CaCO_3$ content
Total N and total C contents (using appropriate methods with adequate detection limits for very low N contents, and making sure to account for inorganic carbonates in the sample when assessing total C)

(Additional options)
Available inorganic N
Available P
Mineralisable N

<u>Recommended vegetation characteristics to sample at the same location (within 2 x 2 m</u> quadrat)
% bare sand
Average sward height
Assessment of NVC community

(Additional options)
Species composition (preferably cover abundance, but presence/absence would suffice)
Above ground biomass

<u>Other recorded information</u>
Slope angle
Slope aspect
Evidence of grazing and type of grazer (cows, sheep, deer, rabbits etc.)
Other observations/field-notes (nearby pollution sources – particularly intensive animal husbandry units and heavy industry, presence of sea buckthorn nearby etc.) – see 'Sand dune vegetation survey of Great Britain' (Dargie, 1993, 1995; Radley, 1994) for field recording sheets from earlier surveys.

References

Dargie, T.C.D., 1993. Sand dune vegetation survey of Great Britain. A national inventory. Part 2: Scotland, Joint Nature Conservation Committee.

Dargie, T.C.D., 1995. Sand dune vegetation survey of Great Britain. A national inventory. Part 3: Wales, Joint Nature Conservation Committee.

Radley, G.P., 1994. Sand dune vegetation survey of Great Britain. A national inventory. Part 1: England, Joint Nature Conservation Committee.

APPENDIX D

Sampling and analysis procedures for measuring soil organic matter content.

Sampling:

Soil sampling is to 15 cm depth, with a known diameter (e.g. 5 cm) core so that an approximate calculation of bulk density can also be made.

Laboratory analysis:

These methods are derived from Ball, 1964.

Equipment required

- Porcelain crucibles
- Desiccator
- Protective gloves and goggles
- Drying oven
- Muffle furnace

Method

Weigh empty porcelain crucibles accurately (usually 4 decimal places). Fill to three-quarters with field-moist soil and reweigh. Place in oven set at 105°C, and leave overnight (16hrs) to drive off moisture. Remove from the oven, cool in a desiccator, and reweigh accurately to 4 decimal places to obtain moisture content. Leave soil in the crucibles and place in the muffle furnace set at 375°C [2] and leave overnight (16hrs) to burn off organic matter. Cool in the desiccator and reweigh to 4 decimal places).

Notes

Always include reference soil samples and include duplicate samples, i.e. one in ten samples to be duplicated.

Reference

Ball, D.F. 1964. Loss-on-ignition as an estimate of organic matter and organic carbon in non-calcareous soils. *J. Soil Science,* 15, 84-92.

[2] 375 °C is used as the furnace temperature as a compromise between burning off all the organic matter and minimising combustion of the carbonates in dune sand which would otherwise give a misleading %LOI calculation. Other methods may use a higher temperature but this is not appropriate.